SOIL EROSION AND TRANSPORT BY NEEDLE ICE: A LABORATORY INVESTIGATION

By

Julia Branson

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School of Geography
University of Birmingham
Birmingham
B15 2TT
U.K

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SYNOPSIS

SOIL EROSION AND TRANSPORT BY NEEDLE ICE: A LABORATORY INVESTIGATION

A series of detailed laboratory experiments have been carried out to investigate the processes of needle-ice growth and the mechanisms by which needle ice incorporates and transports sediment.

The use of laboratory techniques has made it possible to control and monitor the environmental conditions at the soil surface closely, and thus isolate the elements that are important for needle-ice growth. Two types of fine-grained soil sample were used: disturbed (remoulded) and undisturbed. These were taken from sites where needle ice was seen to grow naturally. Remoulding the soil sample affected the growth of needle ice and therefore the amount of sediment uplifted by the ice.

Several types of needle ice were observed: clear, multitiered, crystals with dispersed sediment, soil caps and soil aggregates. Each type was produced under different conditions of soil-surface temperature and moisture. Soil-moisture availability was particularly important in controlling the type and rate of crystal growth. An algorithm has been developed with which to predict the type of crystal that will grow in a given freezing cycle. It is suggested that sediment becomes incorporated into the crystals when there is a disturbance in the environment of needle-ice growth. This disturbance is a result of instabilities in the balance of heat at the freezing front caused when either soil-surface temperature or soil-moisture content fall below a minimum threshold. Typical sediment yields ranged from 0.002 to 2.5 g cm^{-2}. The sediment incorporated into the needle-ice crystals was coarser than the bulk soil from which it was lifted.

The transport of sediment by needle ice was also investigated. It was found that the distance of sediment transport is dependent on the slope angle, length of ice crystal, process of crystal melt, and type of marker particle and soil sample.

A series of simple, statistical models is presented that attempts to predict the growth and morphological effects of needle ice.

TO MY PARENTS AND GILLIAN

Long

I am resolv'd; 't is but a three years' fast:
The mind shall banquet, though the body pine:
Fat paunches have lean pates, and dainty bits
Make rich the ribs, but banquet the wits.

Berowne

I can but say their protestation over;
So much, dear liege, I have already sworn,
That is, to live and study here three years.
But there are other strict observances;
As, not to see a woman in that term,
Which I hope well is not enrolled there:
And one day in a week to touch no food,
And but one meal on every day beside,
The which I hope is not enrolled there:
And then, to sleep but three hours in the night
And not be seen to wink of all the day,
When I was wont to think no harm all night
And make a dark night too of half the day,
Which I hope well is not enrolled there:
O! these are barren tasks, too hard to keep,
Not to see ladies, study, fast, not sleep.

Act 1, Love's Labours Lost

W. Shakespeare

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... 'and anyone else who knows me'

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Chapter 1

INTRODUCTION

1.1 INTRODUCTION

This chapter provides a brief introduction to ground ice, ice segregation and the different types of ice segregation. Following this, a particular type of ice segregation, needle ice, is described, with details of the frequency and occurrence of its growth. The importance of needle-ice growth, as identified by other authors, is also discussed. The aims of the present study, which investigates the growth of needle ice and the lift and transport of sediment by needle ice are outlined. The chapter ends with a summary of the structure of this thesis.

1.2 GROUND ICE

1.2.1 Background to modern ground ice studies

Approximately 25% of the Earth's surface is affected by periglacial conditions (French, 1987a). During the periods of freezing, cold temperatures may penetrate into the ground and result in the formation of different types of frozen ground. This is evidenced in the destruction of roads, displacement of building foundations, misalignment of gates and the cracking of building foundations (Polar Research Board, 1984). These areas experience either seasonal or diurnal intense freezing and thawing.

The expansion of human occupation into the permafrost regions of North America and the U.S.S.R. and the interest in their natural resources within the last 50 years has increased the demand for knowledge of the special environmental conditions in these areas (Williams and Smith, 1989). This has resulted in an expansion of the amount of research concerned with ground ice. Whilst this has largely been concerned with engineering problems and their solutions, a large component of the work has involved assessing the processes involved in the freezing and thawing of soils, and this has formed the basis of modern ground ice studies. This research has relied on the work of field scientists and geotechnical engineers as well as laboratory and theoretical scientists. The surge of interest in periglacial, permafrost and soil freezing processes and forms has been reflected in many texts published over the last 20 years, such as Ives and Barry (1974), French (1976), Washburn (1979), Harris (1981), Polar Research Board (1984), Clark (1988), Williams and Smith (1989) and Black and Hardenberg (1991).

1.2.2 Ground ice

There are large variations in the type of ground ice found in periglacial regions, e.g. segregated ice, pore ice, ice wedges, ice lenses, ice veins and pingo ice (French, 1988). The form of ice which is present in any one location depends on climatic factors, the origin of the water prior to freezing and the process by which water is transferred to the freezing front (Figure 1.1). Most types of ground ice result from four main freezing mechanisms (Harry, 1986):

i) surface water which reaches the freezing front by gravity transfer along cracks and freezes to form single ice veins;
ii) subsurface water which freezes in-situ, forming pore ice in the sediment interstices;
iii) moisture injected under pressure into permafrost sediment, forming bodies of intrusive ice;
iv) water which migrates to the freezing front and forms bodies of intrusive ice.

The present study is concerned with segregated ice which forms by mechanism (iv).

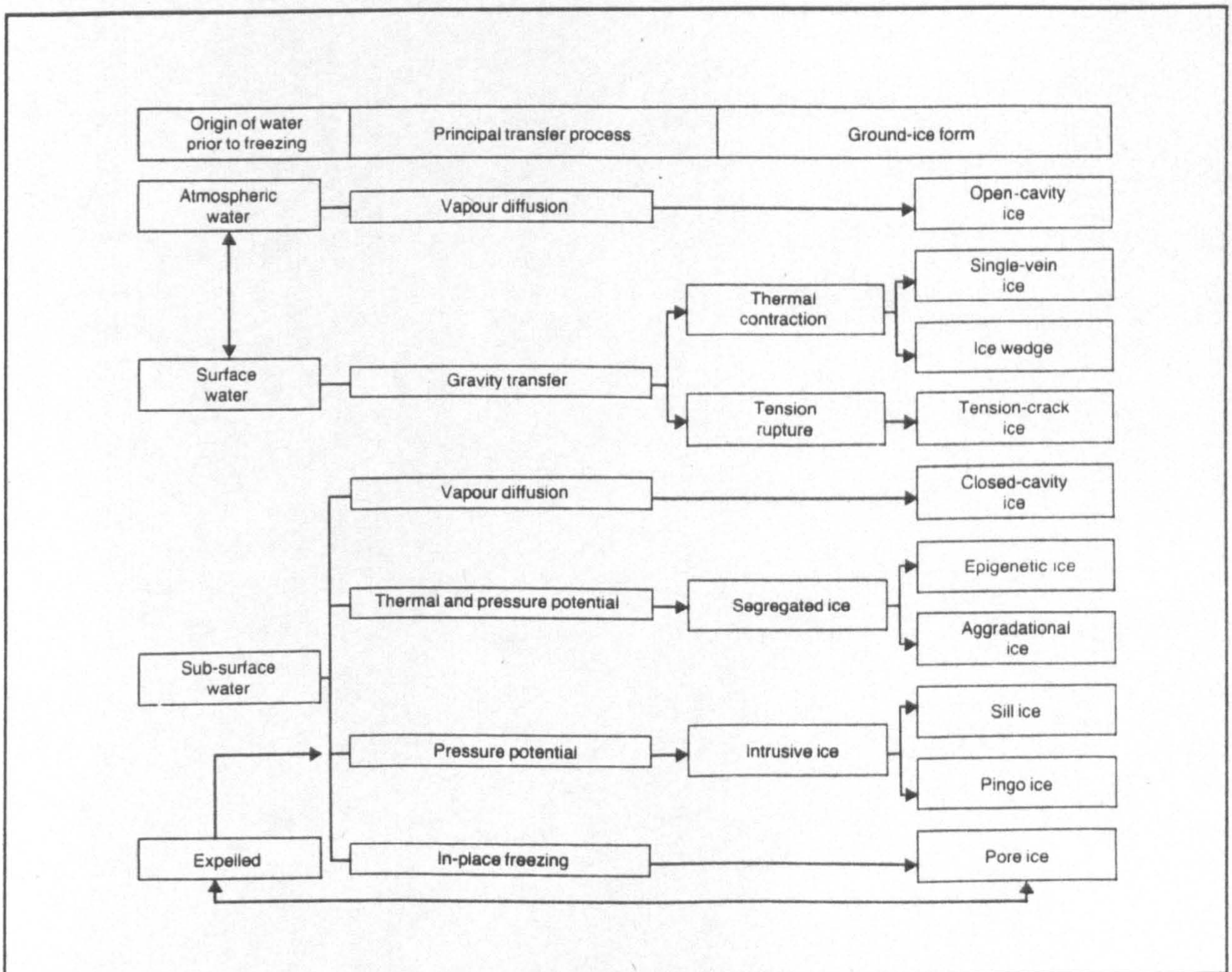

Figure 1.1 : Classification of ground ice according to Mackay (1972).

(Source : French, 1988; p.211)

1.2.3 Segregated ice

Early theories that attempted to explain the action of ice within soils stated that the disturbance (or upheaval) of the soil was caused primarily by the change in volume which occurs when water changes state to ice. Taber (1917, 1918a, 1918b, 1929, 1930), however, suggested that the heaving caused when soil water freezes is greater than the 9% volume increase resulting from the state change. He also observed upheaval in soils which were saturated with benzene or nitrobenzene before being frozen. This is important because these liquids contract on freezing. Thus, frost heaving is due to the accumulation of water and not just fluid expansion. From a series of laboratory experiments Taber was able to demonstrate that water is drawn to the freezing front and forms lenses of segregated ice parallel to the freezing front (Figure 1.2 and Chapter 2). Taber's research led to the concept of ice segregation being introduced. 'Segregation is the increase in water (ice) content in a soil layer produced by water migration to the freezing plane during ice formation' (Outcalt, 1971a; p.394). Water is 'pulled' to the zone of freezing by the process of freezing itself (Chapter 2). 'When this water accumulates as ice, it forces the soil apart, producing expansion of the external soil boundaries, as well as internal consolidation. The dynamic process of ice segregation and the expansion resulting from the freezing of the in situ pore water, together, cause frost heaving' (Polar Research Board, 1984; p.6).

Segregated ice can occur in several forms, for example, as ice lenses within the soil profile or as individual crystals on the soil surface. The type of segregated ice which develops, and particularly its thickness and concentration is dependent upon the amount of freezing, the characteristics of the soil and the moisture availability. The process of ice segregation is discussed further in Chapter 2.

Higashi (1958) identified three different forms of segregated ice. The occurrence of these different types was thought to be related to the rate of frost heaving and the rate at which the freezing front penetrated into the soil. A slow rate of freezing-front migration is necessary for the

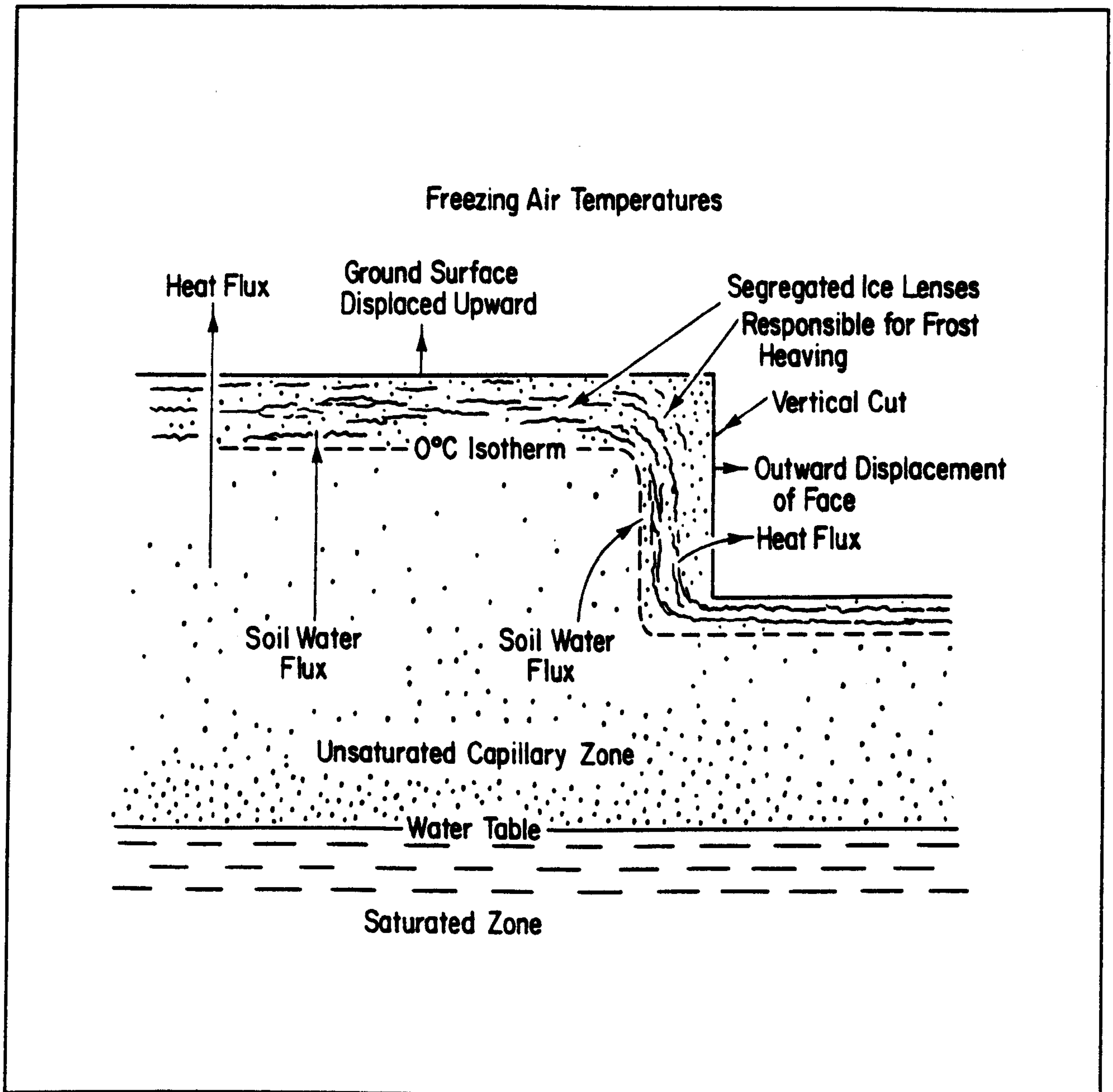

Figure 1.2 : The process of ice segregation.

(Source: Polar Research Board, 1984; p.11)

formation of (ii) and (iii) and a much faster rate is required to produce (i):

i) concrete-type freezing. This produces massive/homogenous frozen soil, whereby the moisture is frozen in the pore space of the soil;

ii) sirloin-type freezing (or ice lenses). This is frozen soil which contains numerous thin layers of ice. The individual lenses of ice are up to 2-4 mm thick and are orientated parallel to the ground surface. Ice lenses are the most common form of ice segregation (Van Vliet-Lanöe, 1985). They grow parallel to the ground surface and perpendicular to the heat flow and usually occur in a series beneath each other. The size of individual lenses and the distance between them is believed to reflect changes in the balance of heat flux at the freezing front (Van Vliet-Lanöe, 1985);

iii) ice filaments or needle ice. This is a transient form of segregated ice which appears as individual crystals on the soil surface. In many areas of the world it is particularly important as an agent of soil disturbance (Chapter 3). James (1972; p.853) suggested that 'needle-ice action constitutes one of the basic frost processes in restricted areas of the highest mountains of Britain and, more especially, in colder regions of the world, where its effects are expressed in landform, microrelief and vegetation patterns'. Needle ice is discussed in further detail in the following section.

1.3 NEEDLE ICE

Needle ice (pipkrake, kammeis, shimobashira, (also see Table 1.1 and Lawler, 1988a) is a form of small scale ground freezing in which crystals grow externally to the ground surface (Plates 1.1 and 1.2). Outcalt (1971; p.394) defined it as 'filaments of ice about 1 mm^2 in cross section and

1.	**English**	Columnar ice	Fibrous ice
		Frost pillars	Glacial grass
		Ice capillary columns	Ice columns
		Ice crystals	Ice filaments
		Ice needles	Ice palisades
		Ice pillars	Icy columns
		Mushfrost	Needle ice
		Needle-like crystals	Needles of ice
		Pinnacles of ice	Prismatic ice crystals
		Spewfrost	Stalactite frost
		Vertical needle crystals	
2.	**Finnish**	Rouste	
3.	**French**	Aiguilles de glace	Glace fibreuse
4.	**German**	Barfrost	Bursteneis
		Effloreszenzeis	Eigentumlichen 'Reif'
		Eisbundel	Eisfilamente
		Eiskrystalle	Eisnadeln
		Haareis	Haarfrost
		Kammeis	Nadeleis
		Stengeleis	
5.	**Japanese**	Shimobashira	
6.	**Polish**	Lod wloknisty (fibrous ice)	Plaskinki ide
7.	**Russian**	Druza	Ledyanye stebelki
8.	**Spanish**	Hielo acicular	
9.	**Swedish**	Pipkrake/pipkrakar	

Table 1.1 : Needle-ice terminology **(Adapted from Lawler, 1988a)**

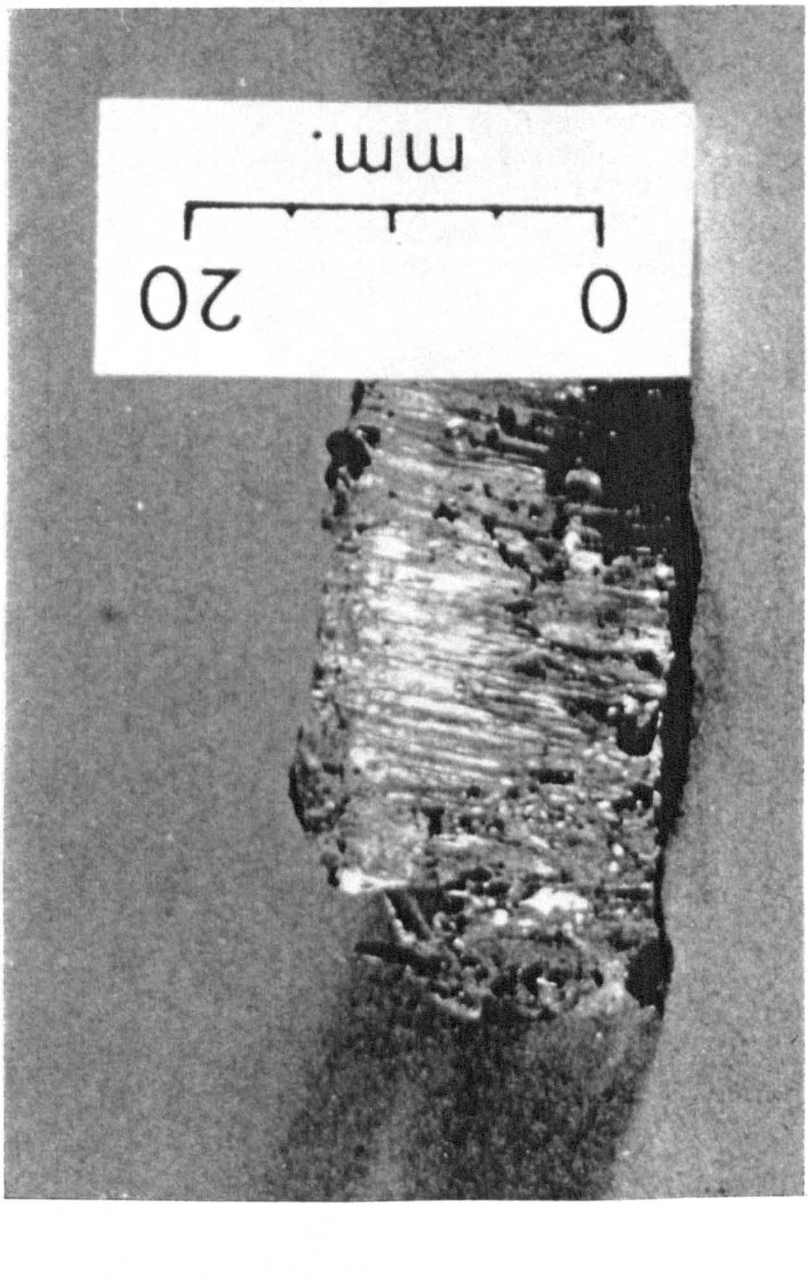

Plate 1.1 : Needle ice.

(Photograph by D.M. Lawler)

Plate 1.2 : Needle ice at a Birmingham field site (ruler is 20 cm long)
Plate 1.3 : Stone uplifted by needle ice at a Birmingham field site

up to 8-10 cm in length, [which] are formed by the segregation of ice near the ground surface during calm, clear winter evenings, when the near-surface soil has been either unfrozen or thawed during the hours of daylight'.

Beskow (1935) observed three different types of needle ice:

i) compact type, where needles formed a complete cover over the soil surface;

ii) porous type, where there were interstices present between the needles;

iii) discontinuous type, where ice only forms in favourable locations.

The growth of needle ice is usually associated with diurnal freeze-thaw conditions affecting loamy soils or plant materials with a sufficient moisture supply (a detailed description of the processes of needle-ice growth is given in Chapter 2). Kay and Perfect (1988) suggested that the thermal conditions during needle-ice growth are such as to prevent the ice from penetrating beyond the first few millimetres of the soil surface. If the ideal thermal conditions for growth are disturbed, however, needle-ice growth ceases (Chapters 3, 6 and 7).

The process of needle-ice growth is thought to be similar to that of the fibrous forms of gypsum, common salt, etc. (Steinemann, 1955). The crystals grow at their bases and are thus pushed upwards out of the growth medium; the growth of the crystals cannot be stopped by wrapping the tops of the fibres to prevent capillary action from the surface. Steinemann argued that evidence to support this hypothesis of growth for needle ice includes the lateral dimensions of the crystals, which approximate the inter-pore distances of the soil. By analysis of thin sections of needle-ice crystals Steinemann determined that their optical axis was perpendicular to the direction of growth, and thus to the temperature gradient.

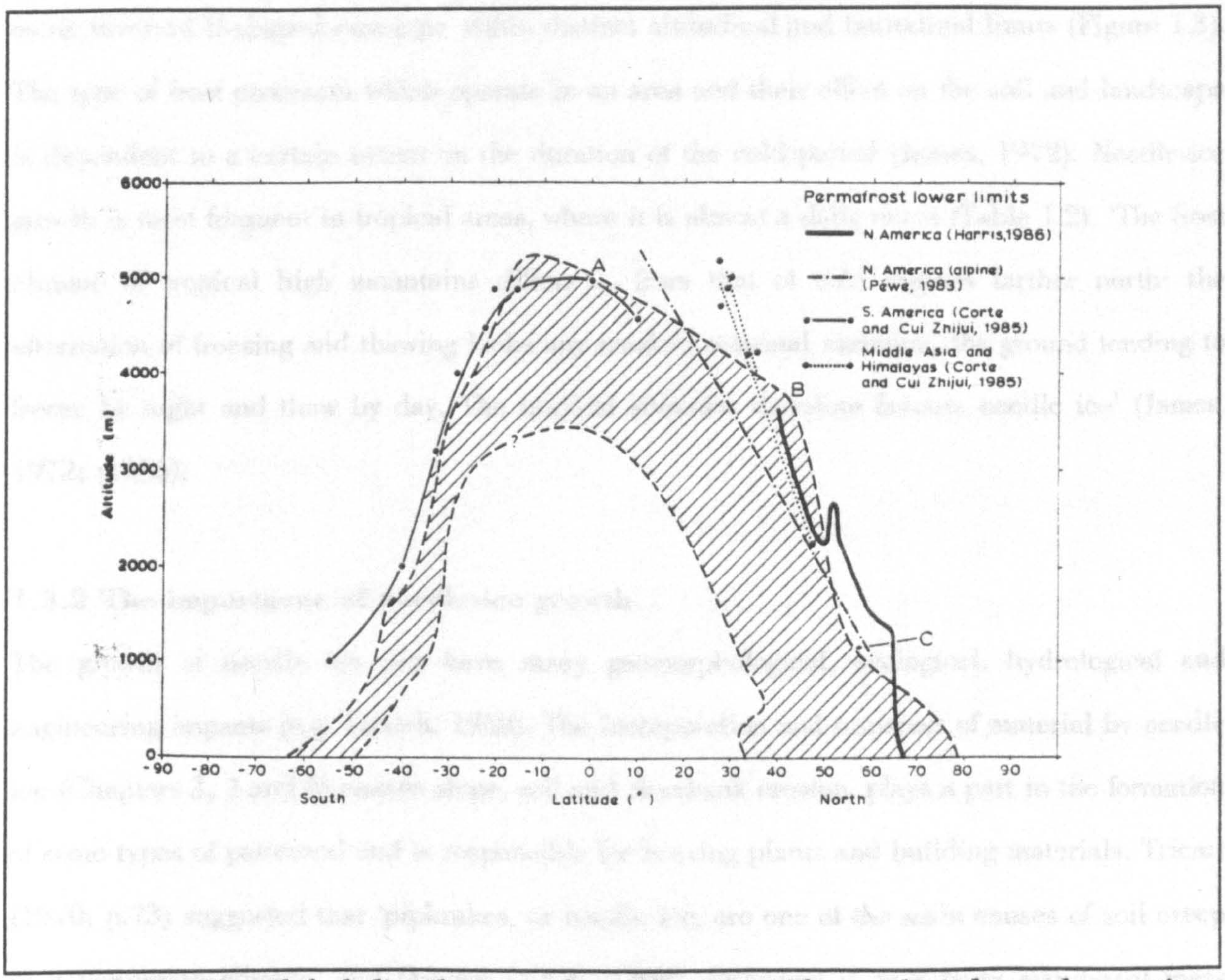

Figure 1.3 : The global distribution of needle-ice incidence, based on observations reported in the literature.

(Source: Lawler, 1988b; p.153)

1.3.1 Occurrence and frequency of needle-ice growth

The growth requirements for needle ice (Chapter 2) are met at all latitudes of the world, especially in humid temperate environments, low altitude sub-arctic and sub-antarctic regions and at high altitudes in the sub-tropics and tropics (Lawler, 1988b, 1989). In a survey of over 100 needle-ice observations worldwide Lawler (1988b) delimited a 'zone of needle-ice potential' as an inverted U-shaped envelope within distinct altitudinal and latitudinal limits (Figure 1.3). The type of frost processes which operate in an area and their effect on the soil and landscape is dependent to a certain extent on the duration of the cold period (James, 1972). Needle-ice growth is most frequent in tropical areas, where it is almost a daily event (Table 1.2). 'The frost climate of tropical high mountains differs ... from that of cold regions farther north: the alternation of freezing and thawing lacks any marked seasonal variation, the ground tending to freeze by night and thaw by day. The tropical situation therefore favours needle ice' (James, 1972; p.856).

1.3.2 The importance of needle-ice growth

The growth of needle ice can have many geomorphological, ecological, hydrological and engineering impacts (e.g. French, 1988). The incorporation and transport of material by needle ice (Chapters 3, 7 and 8) causes slope, soil and riverbank erosion, plays a part in the formation of some types of patterned and is responsible for heaving plants and building materials. Tricart (1970; p.73) suggested that 'pipkrakes, or needle ice, are one of the main causes of soil creep in a temperate climate' and Osburn (1974; p.878) described it as a 'very significant mass wasting mechanism'.

1.3.2a Soil erosion. In many areas, needle ice is responsible for soil erosion (Chapter 3). Pérez (1987a; p.136) stated that 'stone transport by needle ice-activity can be locally very extensive, constituting a major factor of slope erosion'. By lifting material from the main body of the soil (shown schematically in Figures 1.4 and 1.5a) needle ice loosens the soil, thus preparing it for

Table 1.2 : Annual frequency of needle-ice events reported in the literature.

Author	Country	Needle-ice occurrence (events/year)
Gradwell (1957)	South Island, New Zealand	30
Gerlach (1959)	Tatra Mountains, Poland	70 - 82
Brink *et al.* (1967)	British Columbia, Canada	33
Coe (1967)	Mount Kenya, Kenya	Almost every night
Matthews (1967)	Yorkshire, U.K.	8
Outcalt (1969)	British Columbia, Canada	15 - 37
Mackay and Mathews (1974a)	British Columbia, Canada	14
Lawler (1984)	South Wales, U.K.	16[a]
Pérez (1984)	Venezuelan Andes, Venezuela	325 - 350
Smith (1987)	Rocky Mountains, Canada	20

[a]occurrences in 13 months

(Adapted from Lawler, 1988a)

removal either directly as a result of needle-ice induced transport, or indirectly by wind (Davies, 1969) or slopewash (Section 3.3). This process has led to soil deflation in Japan (Ellenberg, 1974) and Iceland (Arnalds, 1987; Arnalds *et al.*, 1987). In such areas prevention strategies, such as soil compaction, have been employed to prevent needle-ice growth (Ellenberg, 1974).

During the winter months needle-ice development in the Omote-Nippon region of Japan causes solifluction (Ellenberg, 1974). This is regarded as an important component of landform development, particularly on unvegetated slopes, as thawing needle ice releases more water than can be retained in the soil. De la Rue (1959) also suggested that needle ice is important in the production of scree.

1.3.2b Patterned ground. In arctic and alpine environments 'needle ice movement is a major influence in the evolution of a wide spectrum of frost-sorted periglacial forms' (Outcalt, 1973;

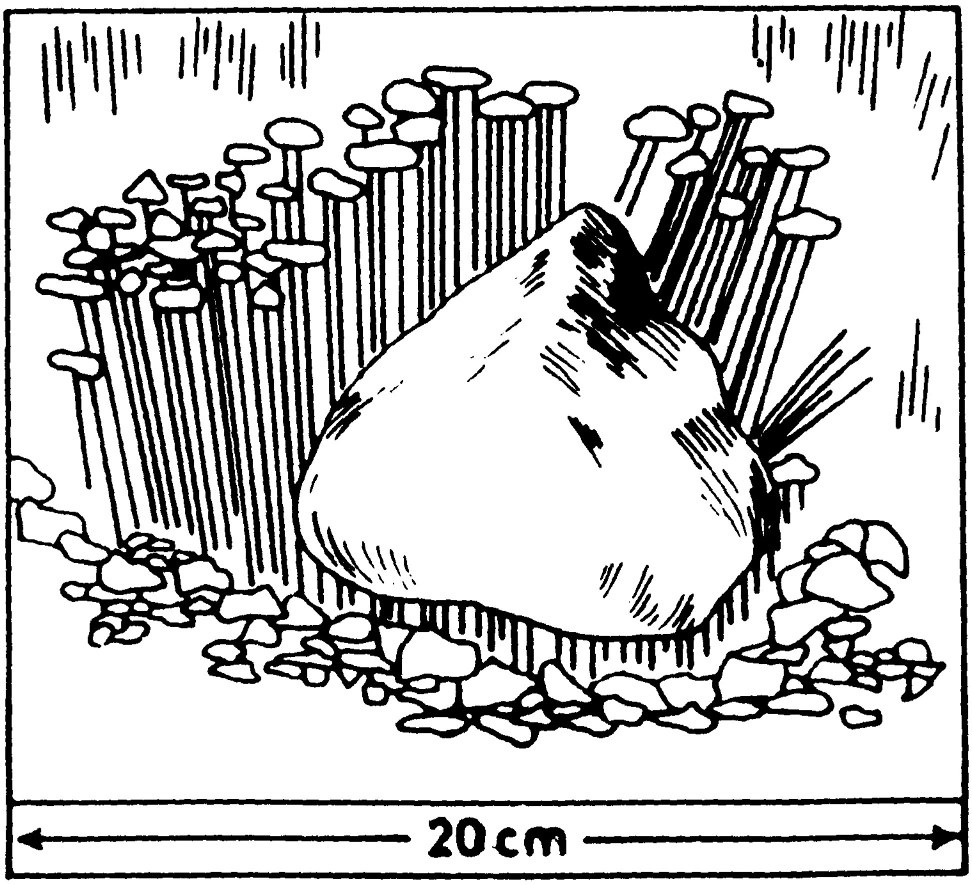

Figure 1.4 : Uplift of soil particles by needle ice

(Source : Derbyshire *et al.*, 1980; p.209)

p.228). These forms may include stone and soil stripes and polygons (e.g. Hay, 1936; Hastenrath, 1973; Mackay and Mathews, 1975; Pérez, 1984). There is no consensus of opinion on the role of needle ice in the development of many of these forms, however, although it is probably as an agent reinforcing sediment sorting by other mechanisms. Brockie (1968), for example, showed that needle-ice activity was predominantly a surface phenomenon which affected only the top 5 mm of the soil. He concluded, therefore, that needle ice only reinforced previously developed patterns of sorted stripes.

Striated soil, also known as needle-ice striped-ground, or raked ground 'produces a miniature pattern characterised by a distinct alignment of the soil surface particles' (Pérez, 1984). The occurrence of this phenomena is widespread, and has been observed in the Drakensberg, South Africa (Troll, 1958), on the sides of Mexican volcanoes (Heine, 1977) and on Iles de Kerguelen (Hall, 1983). The orientation of the stripes does necessarily coincide with the ground slope as with sorted stone stripes (Pérez, 1984). Considerable debate has occurred regarding the mechanism by which striated soil is orientated. The influence of wind direction (Troll, 1958; Schubert, 1973; Beaty, 1974; Hall, 1979) and sun angle (Mackay and Mathews, 1974a, 1975; Pérez, 1984) on needle-ice growth have both been advocated as mechanisms which cause striped ground.

1.3.2c The influence of needle-ice growth on vegetation cover. The damage which needle ice, and other frost effects, cause to cultivated vegetation is known as the 'winter kill'. Heaving by needle ice is frequently as important as the killing of plants by freezing of the plant tissue (e.g. Johnson and Billings, 1962).

Damage as a result of needle-ice growth can result from two factors: soil disturbance and plant 'tugging'. Pérez (1987a; p.136) stated that 'needle ice activity can be so intense in some tropical mountains that it maintains large barren areas' by preventing plant establishment. He suggested that on some occasions needle ice is responsible for 95-99% of seedling deaths.

Needle-ice crystals attach themselves to the plant stalk, grow from below and push the plant out of the ground by the corresponding height of the crystal. Roots are thus progressively exposed, and following several freeze-thaw cycles they are ejected from the ground (Pérez, 1987a). In the valley bottoms of the alpine zone of Mount Kenya it has been argued (Coe, 1967), that vegetation is kept in an immature state due to needle-ice growth. Brink *et al.* (1967) discussed the problems to seedling establishment in British Columbia caused by needle ice. Figure 1.5b shows Haasis' (1923) representation of the heave of seedlings by needle ice.

The existence of a plant cover in some areas can inhibit needle-ice growth (Section 2.3.2d). Vegetation can affect cryogenic processes by restricting heat flow and by the transpirational reduction of free soil water. Johnson and Billings (1962) suggested that the intensity of needle-ice activity on the Beartooth Plateau is not sufficient to affect plant communities which form a complete ground cover.

1.3.2d Engineering implications. The growth and subsequent melting of needle ice can have significant effect on man-made structures. Large amounts of force is produced when the crystals are growing. This force can be responsible for the heaving of roads and foundations. Deckert (1913) suggested that needle-ice growth is 'the most important contributor to the winter break-up and impassability of North Carolina highways'. Bouyoucos and McCool (1928) and Sayward (Pers. Comm. to Lawler) have reported extensive damage caused by the heaving of pavements, roads and foundations by needle ice.

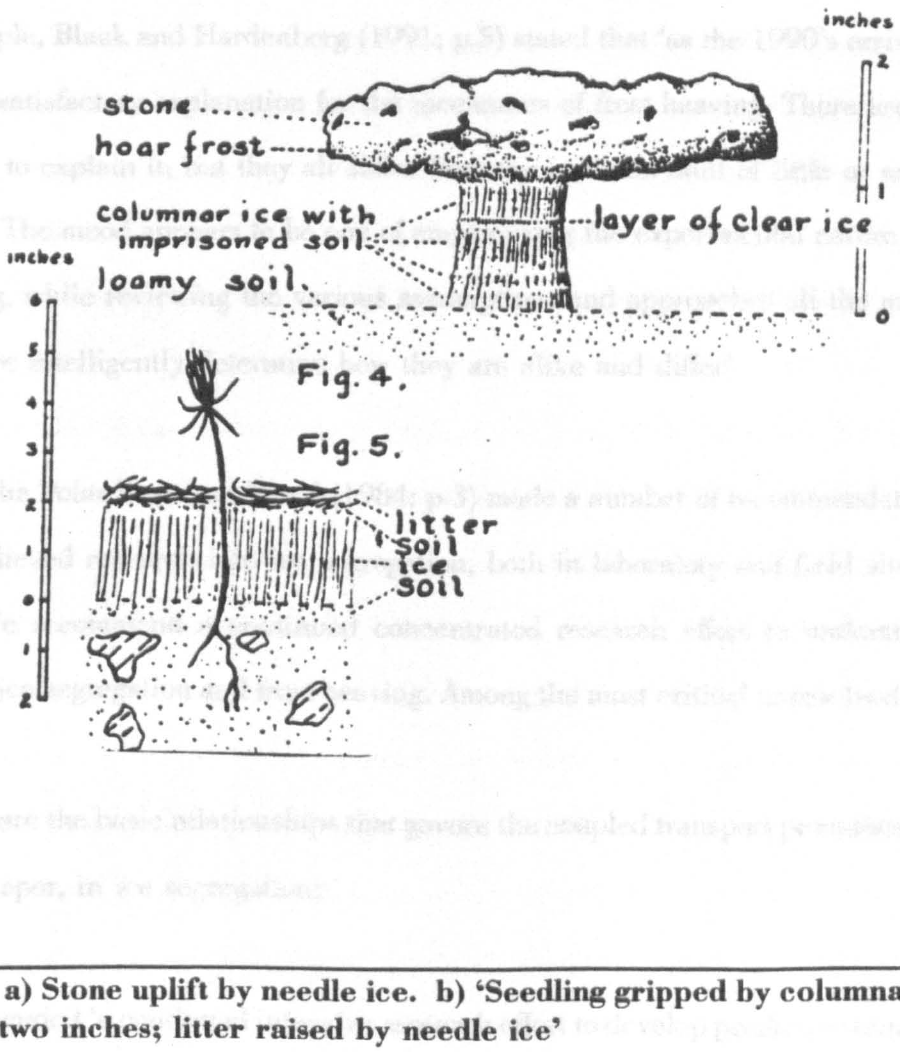

Figure 1.5 : a) Stone uplift by needle ice. b) 'Seedling gripped by columnar needle ice and heaved two inches; litter raised by needle ice'

(Source: Haasis, 1923; p.379)

1.4 AIMS OF THE PROJECT

This section introduces the gaps in needle-ice research which were evident from a review of the needle-ice literature, and the states ways in which the present study aimed to address these gaps.

Several recent publications (e.g. Polar Research Board, 1984; Black and Hardenberg, 1991) have highlighted the need for further research into frost heave and the problems associated with it. For example, Black and Hardenberg (1991; p.5) stated that 'as the 1990's arrive, we find that we have no satisfactory explanation for the mechanics of frost heaving. There are many models that purport to explain it, but they all suffer from the common fault of little or no experimental verification. The mood appears to be one of emphasizing the experimental nature of research on frost heaving, while reviewing the various assumptions and approaches all the models make in order to more intelligently determine how they are alike and differ'

A report by the Polar Research Board (1984; p.3) made a number of recommendations regarding how they believed research into ice segregation, both in laboratory and field situations should progress. 'We recommend a continued concentrated research effort to understand the basic processes of ice segregation and frost heaving. Among the most critical unresolved problems are;

* what are the basic relationships that govern the coupled transport processes (liquid water, heat, water vapor, in ice segregation).'

They recommended 'a continued intensive research effort to develop predictive numerical models that, by simulating ice segregation and frost heaving, can provide a means of consolidating all the processes and interactions involved. This will continue to aid attaining a better and more complete understanding of frost heaving and for assessing its impact in various settings and circumstances.' They suggest that one of the main problems is to determine 'what are the essential and most appropriate parameters required' (for frost heaving) (Polar Research Board, 1984; p.3).

These recommendations have, in part, been taken up with regard to needle-ice growth. The study investigated four main research gaps which are described below.

1.4.1 To improve existing methods used in the laboratory simulation of needle ice

Given the complexity of freeze-thaw processes, and the limited number of occasions that needle ice is produced in Britain under natural conditions, it was decided to base the study on a series of laboratory experiments. Using a simulated freezing and thawing environment provided a great deal of control, and allowed variables that influence needle-ice growth to be closely monitored. Factors such as soil-moisture content and soil-surface temperature could also be manipulated.

To this end, an aim of the project was to improve and extend the methods that have been used in the experimental simulation of frost action (Chapters 4 and 5). Indeed, the Polar Research Board (1984; p.4) stated that 'improved instrumentation to measure the critical phenomena associated with ice segregation and frost heaving is needed'. A greater range of monitoring equipment than had previously been used in the investigation of needle ice (Chapter 4) was used in the present study (Chapter 5). Improvements included the use of continuously-recording soil-moisture blocks, a heave plate and a datalogger (Chapter 5). Greater control over soil surface temperature was also achieved with the use of a microcomputer. Given the possible problems encountered when using remoulded samples of soil (Chapters 5 and 6), undisturbed soil samples were mostly used in this study.

1.4.2 The process of needle-ice growth

Most previous studies of needle ice have concentrated upon the determination of the micro-meteorological and sedimentological controls on needle-ice growth (e.g. Outcalt, 1970, 1971a, 1971b, 1971c; Soons and Greenland, 1971; Meentemeyer and Zippin, 1980, 1981). There now seems to be a general agreement about the main processes and parameters involved (Chapter 2). However, the number of studies which have analysed the rate of crystal growth is limited, and most of those that exist have either mathematically modelled growth rates or indirectly inferred them from temperature data. Few studies have presented data showing patterns of soil moisture and temperature change or heave rates which occur during the growth of ice crystals. Data collected in the present experiments have been tested against existing models of needle-ice growth. An aim of the present project, therefore, was to provide detailed information of the processes which occur both on the soil surface and within the soil profile during the formation of needle ice.

1.4.3 The disaggregation of sediment by needle ice

Despite reasonable attention to the processes of needle-ice growth there have been few studies concerned with the lift and incorporation of material by needle ice. Knowledge of these mechanisms is needed if needle ice is be understood as a geomorphic agent. Outcalt (1971a; p.399) suggested that 'the problem of [soil] banding [within the crystals] may be solved by freezing lab tests, which alter the magnitude of the heat sink and record the structural evolution' [of the needle-ice crystals]. Study of the sediment in needle ice is important because:

i) it gives an indication of the processes which occurred during the growth of the needle-ice crystals;

ii) the disturbance of the soil surface by needle ice is thought to be important for the formation of small-scale landforms, and also gives rise to soil erosion (Chapter 3).

Several hypotheses have been advanced to explain how sediment is incorporated into needle-ice crystals (Chapter 3), but there has been no rigorous testing of these ideas. The existing models and hypotheses have been tested in this study using results from the experiments and simple statistical models have been developed. In attempting to achieve this it is recognised that 'the most difficult combination of related processes to treat, even on a semiquantitative basis, is the heat and moisture flow. This difficulty arises not only from the complexity of the mathematics but also from the lack of experimental measurement of heave rates, heat flow, temperature distributions, and moisture tensions whilst ice lensing is in progress' (Penner, 1959; p.2). However it was intended that the improved instrumentation in the present project would enable some of these gaps to be filled.

1.4.4 Transport of sediment transport by needle ice

Lewkowicz (1988; p.333) stated that 'in terms of needle ice itself, then a good understanding was attained more than ten years ago, but the same cannot be said of the prediction of creep resulting from needle ice'. Further, he commented that there have been numerous observations of needle ice reported, but few field measurements of soil movement due to needle ice. Hayward and Barton (1969; p.3) also recognised a research gap in the study of sediment transport by needle ice, and suggested that 'there is a large gap between understanding how much surface material is moved and knowing how much is shifted'.

The study by Higashi and Corte (1971) is the only laboratory study which has specifically investigated the transport of sediment by needle ice. Only three different slope angles and disturbed soil samples were used. There was thus considerable scope for this study to improve the knowledge of the transport of sediment by needle ice.

Given the limited number of detailed studies on the transport of sediment by needle ice there remain many questions to be answered, namely:

i) the effect of the process of melt on the rate of transport;

ii) the effect of slope on distance and process of sediment transport;

iii) the effect of soil disturbance on sediment transport;

iv) the effect of the size and shape of the material on the rate of transport;

v) how does the location of sediment within the crystal affect distance of transport. All previous models which attempt to represent the transport of sediment by needle ice, (Section 3.3) are based on situation where sediment is present as a soil cap which rests on top of the crystal (Section 3.2). However, experiments which investigated the incorporation of sediment into the needle-ice crystals (Chapter 7) showed that this is not always the case and a large proportion of sediment is incorporated into the crystal. Material incorporated within the crystal will probably be transported different distances, at different stages of the ablation sequence, and possibly by different processes than sediment that is on top of the needle-ice crystals.

1.4.5 Summary of aims

The overall aim of the project was to produce a series of models to represent needle-ice growth and the incorporation and transport of material by needle ice. This was achieved through the following aims:

i) to improve and extend methods previously used for the laboratory simulation of needle ice;

ii) to investigate controls on needle-ice growth sequences by moisture and heat flow;

iv) to investigate the processes by which sediment is lifted by, and incorporated into needle-ice crystals.

v) to examine the processes and rates by which needle-ice crystals melt and transport sediment.

1.5 STRUCTURE OF THE THESIS

This chapter has given a general introduction to ground ice, ice segregation and needle ice. The occurrence, frequency and implications of needle-ice growth have also been discussed. The gaps evident within needle-ice research have been outlined together with the aims of the present study.

The following three chapters examine the present state of needle-ice research through a review of the current literature. Chapter Two outlines the processes by which needle ice grows and analyses the controlling factors. Chapter Three describes the mechanisms by which sediment is lifted and incorporated by needle-ice crystals and analyses how this increases the erodibility of the soil and enabling the transport of material. The processes of sediment transport by needle ice are also discussed. In Chapter Four a review of previous laboratory simulations of needle-ice growth and sediment transport is given. The major themes are identified and case studies of several of the main papers are presented.

Chapter Five describes the methods used for the present series of experiments. The results from these experiments are presented and analysed in the next three chapters.

In Chapter Six a comparison is made between freezing events that produced needle ice and those in which no needle ice grew. The limits of needle-ice growth are then discussed. Following this, the rate of needle-ice growth is described and related to changes in temperature and moisture content at the soil surface. The chapter ends with an analysis of the cover of needle-ice growth over the soil surface with particular reference to the difference in cover between the disturbed and undisturbed samples.

Chapter Seven concentrates on the lift and incorporation of sediment by the needle-ice crystals. Several arguments are advanced to explain the processes by which sediment is incorporated. The selective incorporation of sediment into needle ice is discussed and a comparison made between the results of this study and other investigations.

In Chapter Eight the results from the sediment transport experiments are presented and the affect of various factors on the distance of transport analysed. The processes of needle-ice melt are also discussed.

The results from Chapters 6, 7 and 8 are analysed in further detail in Chapter 9 where the growth and morphological effects of needle ice are represented in a series of multiple regression models. Chapter Ten presents the summary and main conclusions of the research to date and makes recommendations regarding further work in this subject which may be attempted in the future. A summary of the notation used throughout the thesis is given in Appendix 1.

Chapter 2

NEEDLE-ICE GROWTH: A REVIEW

2.1 INTRODUCTION

This chapter discusses the micrometeorological and sedimentological requirements for the growth of needle ice in soil and the processes which occur during its growth. First, a general description of growth is presented. This is based on the work of Outcalt (e.g. 1969, 1970a, 1970b, 1971a, 1971b) and provides a simple model with which to identify the factors necessary for needle-ice growth and the relationships between them. The components of this model and how they can affect needle-ice growth are then discussed in greater detail.

2.2 A SIMPLE 'MODEL' OF NEEDLE-ICE GROWTH

In this section a brief overview of the requirements for needle-ice growth and a simple model of growth as determined by other authors are presented. Following this, the rate of needle-ice growth and the ideal conditions for growth under natural conditions are discussed.

2.2.1 Requirements for needle-ice growth

2.2.1a Meteorological requirements. Outcalt (1971a) stated that for needle ice to grow there must be:

i) a low enough air temperature to supercool the soil surface to the nucleation temperature;

ii) enough soil water to allow ice segregation to occur (the actual amount required is dependent on the characteristics of the particular soil) (Section 2.4.1);

iii) sufficient heat transported to the freezing front, both within the flow of moisture and from the latent heat of fusion, to balance the amount of heat that is removed at the soil surface by cooling. This ensures continuity between the heat flux to, and from, the freezing front.

2.2.1b Sedimentological requirements. In addition to these meteorological requirements, other conditions need to be met for needle-ice growth, some of which are related to the physical and chemical characteristics of the soil. Haasis (1923; p.385), for example, stated that 'evidently the physical and chemical character of any given soil will have a decided influence upon the percolation, activity of capillary movement, and a concentration of soil moisture, and thus upon the amount of heaving damage'.

The medium for needle-ice growth is important in two respects. First, it acts as a location for heat storage (Gilman, 1977) and thus, to a certain extent, controls the energy balance and temperature profile (to a certain extent). Secondly, moisture is stored within the growth medium. Different properties of the soil control each area of influence.

For needle-ice growth soils must be frost susceptible: loams, loess and volcanic materials are ideal growth media. A frost susceptible soil is defined as a 'soil in which significant detrimental ice segregation occurs when the requisite moisture and freezing conditions are present (Johnston, 1981; p.xx). The relative frost susceptibility of soils has been investigated by Taber (1929), Beskow (1935) and Kaplar (1968), among others. Taber (1929) conducted a series of experiments to determine the sedimentological controls on ice segregation in terms of the size of soil particle, and size and percentage of pores. He observed that 'segregation occurs readily if the particle diameter is less than a micron, and under favourable conditions where particles are somewhat larger'. Casagrande (1932) suggested that 'under natural freezing conditions and with a sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than 3% of grains smaller than 0.02 mm and in very uniform soils containing more than 10% smaller than 0.02 mm. No ice segregation was observed in soils containing less than 1% of grains smaller than 0.002 mm even if the groundwater level was as high as the frost line'. Johnston (1981; p.142), argued, however, that 'the 3% finer by weight than 0.02 mm criterion is not a sharp dividing line. For example, laboratory studies have shown that some gravelly soils, which have about 1% of their particles finer than 0.002 mm, heave significantly and that some sandy materials having up to 20% finer than 0.02 mm do not exhibit undesirable frost heave characteristics'.

The grain-size distribution of the soil is important because the critical moisture content for ice segregation is controlled by the pore radius of the soil (Section 2.4.2). If the pore radius is small then the soil has a low hydraulic conductivity, and moisture migration to the freezing front is inhibited. With large pores, however, there is insufficient suction potential to allow the flow of water to the freezing front (Washburn, 1973). Van Steijn (1977; p.274) argued that loess is an ideal medium for needle-ice growth 'because it is fine enough to maintain a continuous waterfilm, but not so fine that flow is almost impossible because of the high hydraulic gradients which are required'. Soil-surface cover and roughness also need to be low as they influence soil-surface temperature and moisture content (Section 2.3.2d).

2.2.2 The process of needle-ice growth

During evening the temperature at the soil surface decreases as a result of radiative cooling. If the temperature reaches the ice nucleation point (Section 2.3), ice begins to form at the soil surface. If there is sufficient moisture available in the soil then ice segregation commences

(Figure 1.2). As a result of ice formation, a tension gradient is believed to establish in the soil, and water is 'pulled' to the freezing front from further down the soil profile (Section 2.4.3). Burt (1981) argued that the migration of moisture in the soil occurs as a result of the low potentials which exist in the frozen soil; at the freezing front moisture flows preferentially to the ice which is already present. The moisture also transports heat to the freezing front. As long as there is sufficient heat arriving at the freezing front to balance that being removed at the soil surface then the freezing front remains stable and ice segregation continues, producing needle ice (Sections 2.4 and 2.5). Needle ice grows rather than ice lenses because of the slow cooling rate, and also, at the soil surface there is usually no overburden pressure, and the needles can thus normally grow upwards without restriction (Chapter 1; Higashi, 1958). It has been suggested that the thickness of the individual needles is related to the pore size of the growth media (Section 1.3; Steinemann, 1955).

2.2.2a The rate of needle-ice growth. The rate of needle-ice growth is determined by the heat transfer in the soil, which in turn, is a function of the soil-moisture content and the soil-surface temperature (De Vries, 1963; Gilman, 1977; Davidson, 1978). As long as the freezing front is stable needle-ice growth continues (Section 2.5). Fujita (1936) stated that the rate of needle-ice growth is controlled by the availability of moisture at the freezing front, and that a steep soil temperature gradient will increase the growth rate. Similarly, Ozawa and Kinosita (1989) suggested that the growth rate of segregated ice is proportional to the degree of supercooling, which is in turn determined by the rate of heat conduction. There are few published figures of the rate of needle-ice growth, presumably because until recently measurement has been difficult (Chapter 5). Rates of needle-ice growth from several studies are shown in Table 6.1.

2.2.3 The ideal conditions for needle-ice growth

The ideal climatic conditions for needle-ice growth can be summarised as a negative thermal radiation balance, low sky radiant temperature and a steep gradient of vapour pressure from the wet soil surface to the dry air (Outcalt, 1971a).

Outcalt (1971a) and Meentemeyer and Zippin (1980) determined that the passage of a cold front during the winter months in Vancouver and the Georgian Piedmont respectively tends to produce needle ice. First, large amounts of rain fall, producing adequate soil moisture, followed by a decrease in temperature and clearing weather (which results in advective cooling). Similarly, Le Conte (1850) reported that needle-ice growth was most prolific when a warm rainy period terminated in clear freezing weather.

Lawler (1988b; p.155) suggested that river banks provide an ideal locality for needle-ice growth because of the generally high moisture content of the bank materials replenished by throughflow and bank storage, the increased probability of lower temperatures due to 'the ponding up of katabatically draining cold air on radiation nights' and limited vegetation cover. Pérez (1987a; p.149) found that needle-ice growth in the Venezuelan Andes was more frequent, and the effects more intense, on lower slopes with a north-west aspect. He argued that 'cold drainage ... enhanced the growth of needle ice in lower slope positions'.

2.2.4 Summary

From the above discussion it is evident that there are three stages to be considered in the analysis of needle-ice growth:

i) the nucleation of ice in soil;

ii) ice segregation;

iii) the continuity of growth.

In the next three sections these stages are described in turn and the factors and processes which affect the ideal conditions are discussed (see also Figure 2.1). Outcalt (1969; p.1377) stated that 'gross environmental control [on needle-ice growth] is exerted by the state of the energy and mass transfer system above the surface'. In this examination of ice nucleation and needle-ice growth, therefore, it is necessary to discuss these energy and mass transfers. The next section discusses the nucleation of ice and how it is controlled by the energy balance of the soil surface.

2.3 THE NUCLEATION OF ICE IN SOIL

Ice nucleation is the process by which small particles of ice (nuclei) are produced which then grow to form ice crystals (Brophy *et al.*, 1964; Fletcher, 1970; Hobbs, 1974). Embryos form at temperatures just below the freezing point of water. The thermal energy conditions favour their disintegration, however (Williams and Smith, 1989), and thus a further temperature depression is considered necessary to produce stable nuclei that are able to grow. The temperature at which this occurs is termed the nucleation temperature (T_N) (Figure 2.2). The value of T_N depends upon the characteristics of the growth medium, and in pure water it can be as low as -39°C because the growth of ice must be initiated by molecules of water which combine to produce an 'ice embryo' that grows spontaneously (Hobbs, 1974). This is known as homogeneous nucleation. Foreign particles, however, may act as nuclei in a liquid, and facilitate heterogeneous nucleation (Hobbs, 1974). Thus, the T_N can be greater than that for pure water (Martin, 1959).

In soil, nucleation is complicated by the characteristics of the soil itself, particularly its texture (Martin, 1959). The probability of nuclei formation is controlled by the temperature within the soil and the ability of moisture to move towards the location of the suitable temperature. In soils, water migration is limited because the water exists in the pores between soil particles, and, in the case of silts and clays, a proportion may be adsorbed onto the soil particle (Beskow, 1935;

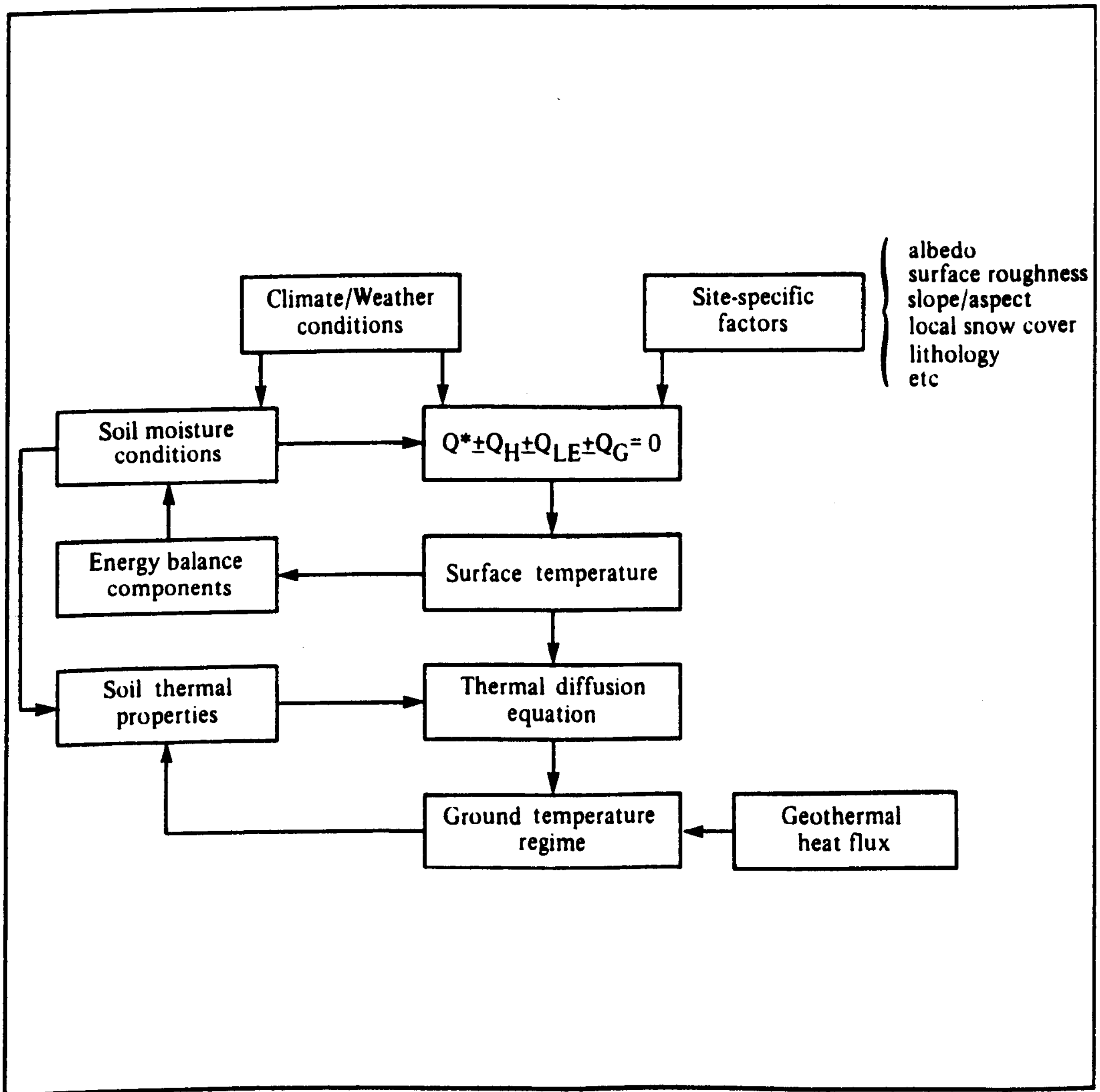

Figure 2.1 : A flow diagram of climate-ground thermal interaction

(Source: Williams and Smith, 1989; p.66)

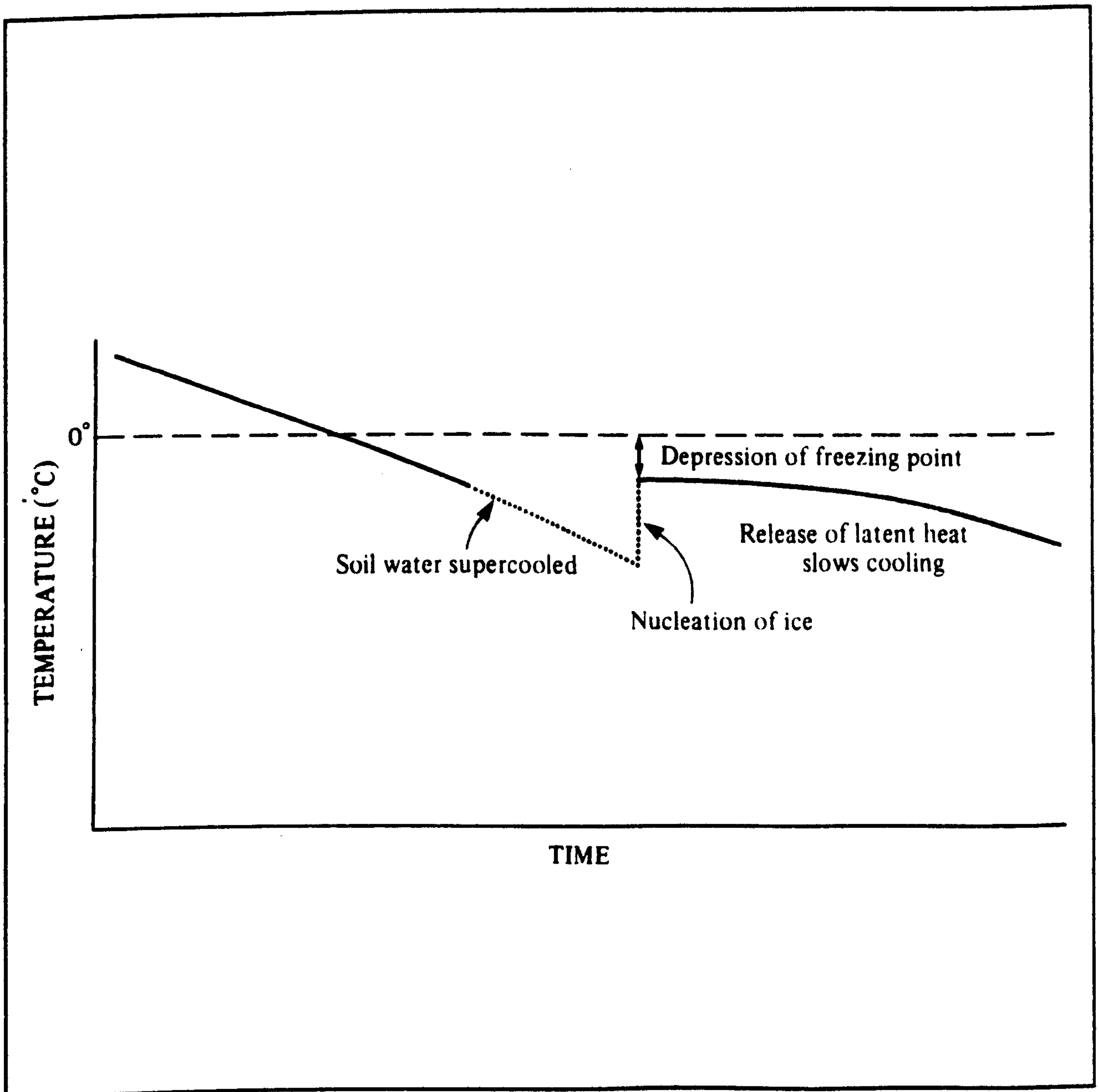

Figure 2.2 : Cooling of a soil sample under a constant rate of heat extraction. (Dotted line represents supercooling.)

(Source: Williams and Smith, 1989; p.175)

Ward and Robinson, 1990; Williams and Smith, 1989). Movement in both instances is limited because of the tensions developed at the water-soil contact. On the basis of field observations Outcalt (1971a) suggested that to initiate needle-ice growth the soil-surface temperature needs to be as low as -2°C. The growth of the nucleus, once formed, can occur at a temperature greater than T_N, but not exceeding 0°C.

2.3.1 Surface radiation budget and energy balance

Ice nucleation occurs when the equilibrium temperature ('that temperature which a surface must reach to balance the heat flow across it' (Outcalt, 1969; p.1377)) reaches the ice nucleation temperature.

Surfaces heat up and cool down in response to changes in their energy balance. These changes are brought about initially by fluctuations in components of the radiation budget. The net all-wave radiation flux (Q^*) represents the most important exchange of energy within the soil-air system, as it indicates the size of the energy source or sink (Oke, 1987). During daytime the radiation budget can be represented by

$$Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow) \tag{2.1}$$

$$Q^* = K^* + L^* \tag{2.2}$$

where $K\downarrow$ and $K\uparrow$ are the incoming and outgoing short-wave radiation respectively, and $L\downarrow$ and $L\uparrow$ the incoming and outgoing long-wave radiation. K^* and L^* represent the net short-wave and long-wave radiation.

At night no solar radiation reaches the soil surface, so the budget is represented as

$$Q^* = L\downarrow - L\uparrow \tag{2.3}$$

$$Q^* = L^* \tag{2.4}$$

Typically there is a radiant surplus during the day and a deficit during the night.

The net all-wave radiation flux is the basic input into the surface energy balance (Figure 2.3). The surface radiation imbalance is accounted for at any one time by convective heat exchange as sensible (Q_H) or latent heat (Q_E), conduction to/from the soil Q_G and changes in the storage of heat in the atmosphere and ground ΔQ_S.

$$Q^* = Q_H + Q_E + Q_G + \Delta Q_S \tag{2.5}$$

During the day there is a surplus of incoming radiation. The energy budget is thus balanced by the absorption of heat by the atmosphere and soil surface. In the evening the deficit of radiation is balanced by the removal of heat from the soil and atmosphere (Oke, 1987). The proportions of heat absorbed or released by the Q_H, Q_E and Q_G components depends on the ability of the soil and atmosphere to transfer heat. It is the removal of heat from the soil surface during the evening which causes the soil to cool and ice nucleation to occur. This is why needle-ice growth is a temperate zone phenomenon; in warmer regions the radiative cooling is never sufficient to balance the (daily) inputs of energy.

The air-ground energy balance equation for a soil surface (after Outcalt, 1971a) can be written as

$$\sigma(T_a + 273.15)^4 - \sigma(T_s + 273.15)^4 + Q_S + Q_H + Q_E = 0 \tag{2.6}$$

Where T_a and T_s are sky and surface temperatures (°C) respectively, and σ the Stefan-Boltzmann constant. All the components of the energy balance equation vary with sky temperature and the

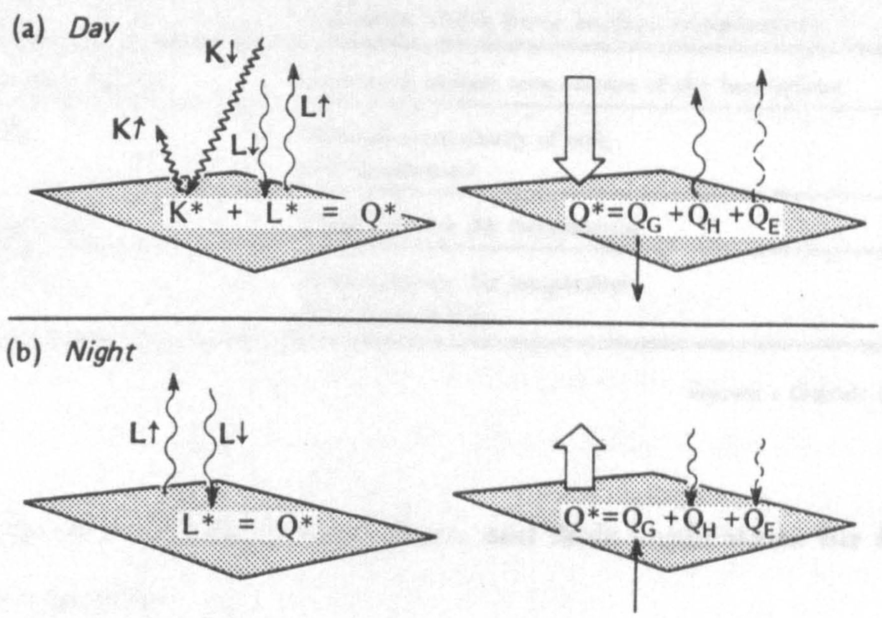

Figure 2.3 : Schematic summary of the fluxes involved in the radiation budget and energy balances of an ideal site; (a) by day and (b) by night.

(Source: Oke, 1987; p.26)

variables shown in Table 2.1 (and discussed below). If these variables are known then Outcalt (1971a; p.295) argues that there is 'one and only one unique surface temperature that will balance the heat flux equation'.

Other factors which influence the rate of heat removal and thus soil-surface temperature are discussed in the next section.

Table 2.1 : The external variables which affect soil-surface temperature

Component	Variables which force surface temperature
Thermal radiation balance	Equivalent radiant temperature of sky hemisphere
Soil heat flux	Thermal conductivity of soil; Soil temperature
Sensible heat flux	Wind velocity; Air temperature
Latent heat flux	Wind velocity; Air temperature Relative humidity

Source : Outcalt (1971a; p.395)

2.3.2 Controls of soil-surface temperature, and their implications for ice nucleation and needle-ice growth

Several factors influence the temperature at the soil surface. These include the microclimate at the soil surface and soil characteristics.

2.3.2a Wind speed and direction. Wind speeds can influence needle-ice growth, the effect is specific to one site and at one time. High wind speeds enhance convective cooling and evaporation, and thus cause the freezing front to descend rapidly into the soil before ice segregation can occur. Wind may also encourage turbulent mixing with warmer air aloft on radiation nights. Observations in Vancouver (Outcalt, 1970a) showed that needle-ice growth terminated when wind velocity 0.6 m above the ground was greater than 150 cm s^{-1}. Optimum needle-ice growth in the same location was calculated to occur at a velocity around 80 cm s^{-1}.

Wind can often have a different effect by influencing soil-surface temperatures. Ellenberg (1955) determined that on the Kanto plains (Japan) a north-north-west wind caused a temporary warming of the air closest to the ground and stopped the growth of needle ice.

2.3.2b Atmospheric humidity. Relative humidity influences the length of the needle ice grown in a given freezing event (Outcalt, 1970a; Meentemeyer and Zippin, 1980). As relative humidity increases, radiative heat losses from the soil surface are reduced and the rate of needle-ice growth declines (unless the heat loss was initially large and thus the growth rate may increase).

2.3.2c Albedo and emissivity. Albedo is 'the ratio of the amount of solar radiation reflected by a body to the amount incident on it' (Oke, 1987; p.400). Albedo is controlled by a number of factors including the colour, texture, roughness and moisture content of the soil (Table 2.2). Dark-coloured soils absorb radiation more effectively than lighter soils and thus have a lower albedo. In a ploughed field the short-wave radiation is more likely to be absorbed by the edge of the ploughed troughs, before being transmitted to the atmosphere. Thus, the absorption is increased, and the albedo decreased, in relation to a level field (Oke, 1987).

The emissivity is the 'ratio of the total radiant energy emitted per unit time per unit area of a surface at a specified wavelength and temperature to that of a black body (which absorbs all radiation) under the same conditions' (Oke, 1987; p.400). A soil with a high emissivity cools faster than a soil with a low emissivity. Thus, the ice nucleation temperature will be reached earlier in soils of high emissivity (all other things being equal).

Table 2.2 : Typical albedo and emissivity values for different surfaces

Surface		Albedo	Emissivity
Dark, wet soil		0.05 - 0.40	0.90 - 0.98
Light, dry soil		0.20 - 0.45	0.84 - 0.91
Grass	Long (1.0 m) Short (0.02 m)	0.16 - 0.26	
Agricultural crops		0.18 - 0.25	0.90 - 0.99

Adapted from Oke (1987; p.12)

2.3.2d Soil-surface characteristics. Needle-ice growth is sensitive to boundary conditions (i.e. the soil-surface characteristics), and is thus open to human manipulation (Outcalt, 1971b). Vegetation cover, for example, modifies the energy exchanges between the soil-atmosphere system and thus affects ice nucleation and needle-ice growth. The energy balance of a soil-plant-air system can be written as follows (Oke, 1987; p.110)

$$Q^* = Q_H + Q_E + Q_S + \Delta Q_P \tag{2.7}$$

where ΔQ_P is the net rate of energy stored due to photosynthesis.

The density of vegetation cover is particularly important. Long-wave radiative cooling may be inhibited by dense vegetation and prevent the formation of a freezing front in the soil, thus needle-ice growth will not occur (e.g. Gradwell, 1955). Placing a mulch on the soil surface (e.g. hay, straw, sawdust, gravel, aluminium foil) may also affect the soil microclimate (West, 1932; Van Duin, 1954). Covering the soil can prevent excessive cooling (and thus prevent the ground reaching the nucleation temperature), influence albedo and reduce evaporation (Fukuda, 1936; Sayward, 1979). Gradwell (1955) determined that needle ice grown under snow cover was shorter than that grown on a snow-free area.

Using a mathematical model of needle-ice growth Outcalt (1971b) predicted that the maximum length of needles produced in one freezing period decreased as the roughness height of the surface increased. Activities such as ploughing a field will increase ridge relief, and will thus have a significant effect on needle-ice growth (Outcalt, 1971b).

2.3.2e The water balance. Soil moisture is important in a consideration of the surface energy balance because it not only provides the water for ice crystallization and segregation but also affects the partitioning of radiative, conductive and convective heat transfer (Oke, 1987). The water balance of the soil is controlled by inputs of moisture from precipitation and outputs by evaporation (which is in turn influenced by radiation, windspeed and relative humidity).

Oke states that adding moisture to the soil may alter albedo and thus change K^* and Q^*. The thermal properties of a soil are thus influenced by soil moisture (Figure 2.4).

Soils with a high diffusivity change temperature rapidly to match the surroundings. The variation in diffusivity with soil-moisture content and temperature depends on the relationship between thermal conductivity and heat capacity. When water is added to dry unfrozen soil the thermal conductivity increases more rapidly than the heat capacity. Thus diffusivity increases as more water is added (Oke, 1987). At high soil-moisture contents the thermal conductivity increases more slowly with increasing water contents. The heat capacity, however, continues to increase at a constant rate, and therefore diffusivity may decrease. The diffusion of heat within a sample is thus impeded at low water contents by the low thermal conductivity, and at high moisture contents by a large heat capacity (Figure 2.4) (Williams and Smith, 1989).

For a given amount of heat supplied, the change in the soil-surface temperature (ΔT_S) is greater in a soil with a lower heat capacity. For example, 'dry soils' have a heat capacity of 1.0 to 1.5 MJ m^{-3} K^{-1} (at temperatures near to 0°C), whilst the heat capacity of water (at 0°C) is 4.2 MJ

m^{-3} K^{-1} (Williams and Smith, 1989). Thus, the heat capacity of the soil increases significantly when wet (Chapter 2 and Williams and Smith, 1989);

The water balance of a soil can be written as

$$p - E + \Delta r + \Delta S \qquad (2.8)$$

Where p is precipitation, E is evapotranspiration, Δr net runoff, and ΔS changes in the soil-moisture content (Figure 2.5).

Soil moisture is supplied from a variety of sources. Tufnell (1971) reported that water for needle-ice growth was provided from snow melt, and Satake (1977) noted that moisture was supplied from adjacent puddle water. In a slope system, the moisture supply is dependent on recent precipitation events, whilst on a river bank, the period lapsed since the last high stage event may also be important.

The water balance of the soil-plant-air system can also be represented by Equation 2.8 (Oke, 1987), but here, ΔS is the net water storage in the air, soil and by plants (both within the plant and precipitation intercepted by the leaves) (Figure 2.5). If advection is present, an additional term, A should be included to account for the exchange of moisture horizontally.

2.4 ICE SEGREGATION

For needle ice to grow once ice nucleation has occurred, the freezing front should be stable to allow ice segregation to occur. To achieve this there must be a flow of soil moisture to the freezing front, from the unfrozen soil below, to compensate for the water which is frozen at the soil surface. The flow of moisture also provides a source of heat to the soil surface. If there is

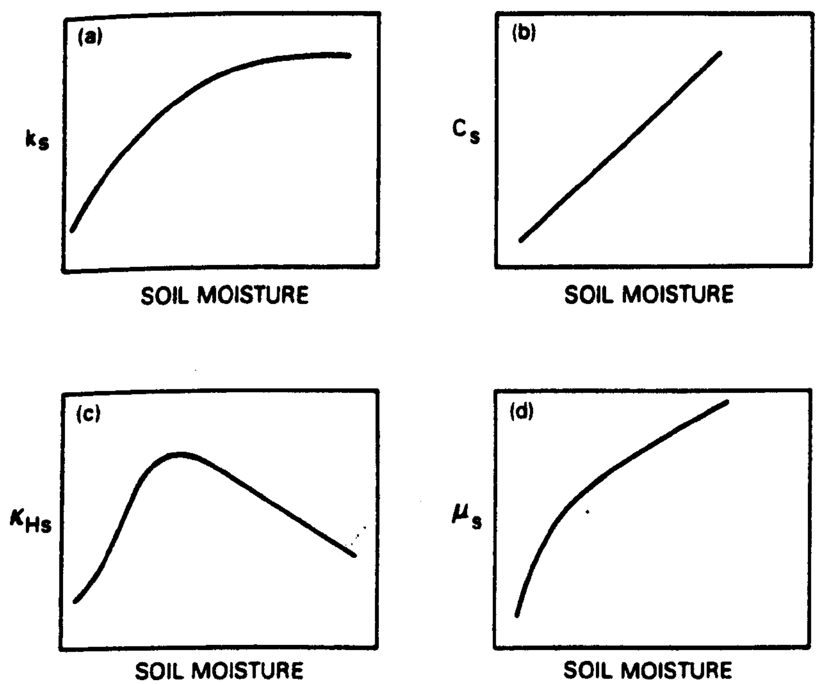

Figure 2.4 : Relationship between soil moisture content (a) thermal conductivity, (b) heat capacity, (c) thermal diffusivity and (d) thermal admittance.

(Source : Oke, 1987; p. 45)

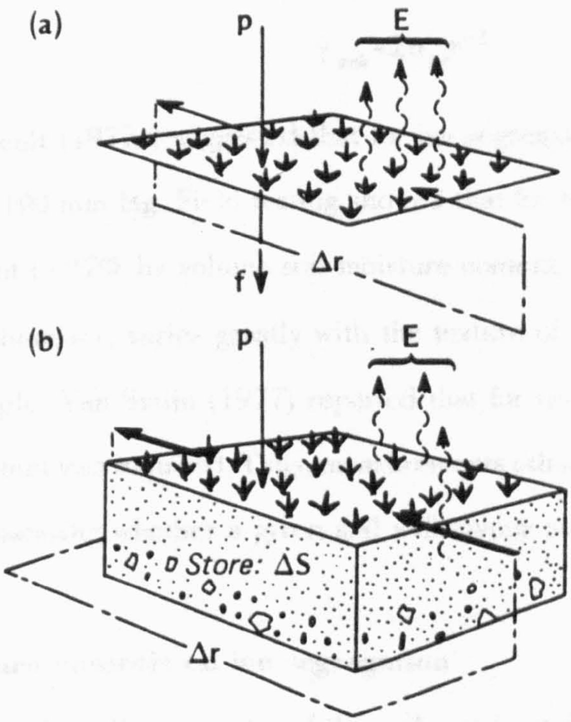

Figure 2.5 : Diagrammatic representation of the components of the soil water balance of (a) a natural surface, and (b) a soil-plant column.

(Source : Oke, 1987; p.30)

insufficient water at the freezing front then ice segregation cannot occur. This section discusses the critical soil-moisture content required for ice segregation, the controls of soil texture upon soil-moisture content and moisture migration within the soil.

2.4.1 The critical soil-moisture content required for segregation

Outcalt (1971a) stated that the critical soil-moisture content (γ_{crit}) for ice segregation to commence is a function of the surface tension between the ice and water (σ_{iw}) and the pore radius (r), such that

$$\gamma_{crit} = 2\sigma_{iw} r^{-1} \tag{2.9}$$

For his soils Outcalt (1971a) suggested that for ice segregation to occur the soil water tension must not exceed 100 mm Hg. Field testing showed that for this particular sandy loam, 100 mm Hg was equivalent to 27% by volume soil-moisture content. The actual amount of water at 100 mm Hg tension, however, varies greatly with the texture of the soil (Meentemeyer and Zippin, 1981). For example, Van Steijn (1977) reported that for needle ice to grow in loess only 20% soil-moisture content was required. Thus, measurements other than soil-moisture content are also required when assessing whether a given soil will favour needle-ice growth.

2.4.2 Soil texture controls on ice segregation

Soil texture, particularly the geometry of the soil matrix and particle-size distribution are often referred to as indices of 'frost heave susceptibility' (Section 2.2.1b). The texture of a soil determines its porosity which determines the thermal properties of the soil. Soil texture ultimately controls the ability of the soil to store water. Thus, 'an analysis which accounts for the action of moisture and texture variables ... is apparently the only way to resolve the threshold limits which these factors impose on ice formation' (Meentemeyer and Zippin, 1981; p.115). The soil texture limits required for needle-ice growth according to Meentemeyer and Zippin are shown in Table 2.3.

Table 2.3 : Minimum soil-moisture content required for needle-ice growth in soils of different textures

Soil sample	Soil-moisture content (%)	Soil texture		
		% Fines	% Clay	% Silt
1	19.5	24.1	9.1	15.0
2	20.2	20.7	6.2	14.5
3	21.1	17.7	5.2	12.5
4	22.6	11.4	3.9	7.5
5	24.7	7.9	2.6	5.3

Source: Meentemeyer and Zippin (1981; p.118)

Experiments by Meentemeyer and Zippin (1981) have shown that as soil texture becomes coarser the water-holding capacity of the soil is reduced, along with its ability to transmit water through soil pores. The moisture content needed to produce needle ice seemed to increase as the percentage of fines in the soil decrease. Finer soils are therefore more susceptible to needle-ice growth. Clay minerals, however, immobilise the water adjacent to the adsorbing surface (e.g. Williams and Smith, 1989; Figure 2.6). The permeability (and hence ability of the soil to supply water for ice segregation) is thus reduced. Above a certain percentage of fines, therefore, needle-ice growth may not be possible, and this explains why Linell and Kaplar (1959) found a lack of heave in fine clay soils. Price (1972) also argued that the transfer of moisture in clays was too slow to facilitate needle-ice growth. The rate of soil heave may also be influenced by soil texture (e.g. Figure 2.7).

2.4.3 Moisture migration during needle-ice growth

For needle-ice growth to continue once ice segregation commences it is necessary for moisture to migrate to the location of freezing. Often this is difficult to show, however, because there are limited field data of soil-moisture profiles.

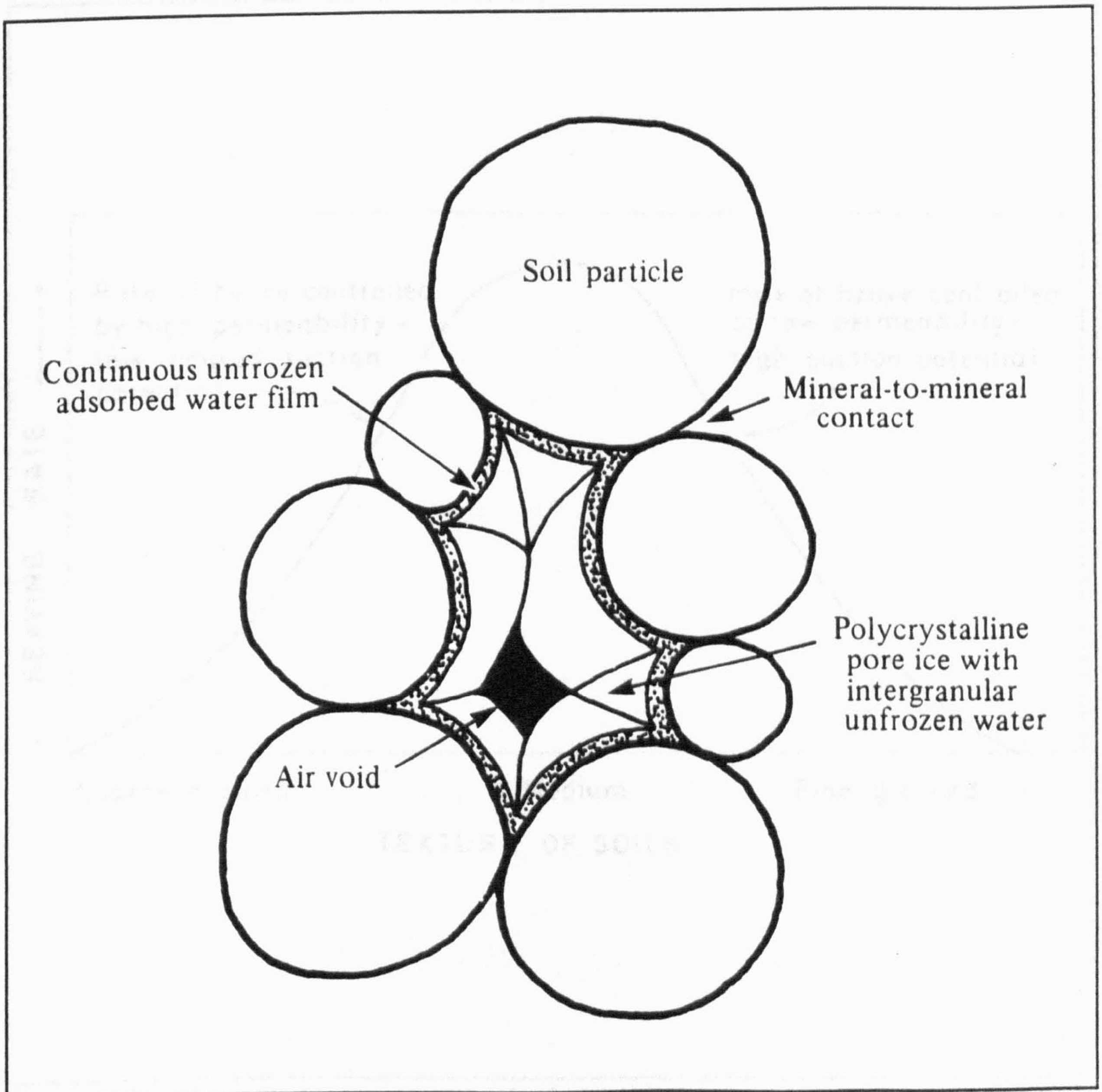

Figure 2.6 : Structural elements of frozen granular soil

(Source: Williams and Smith, 1989; p.238)

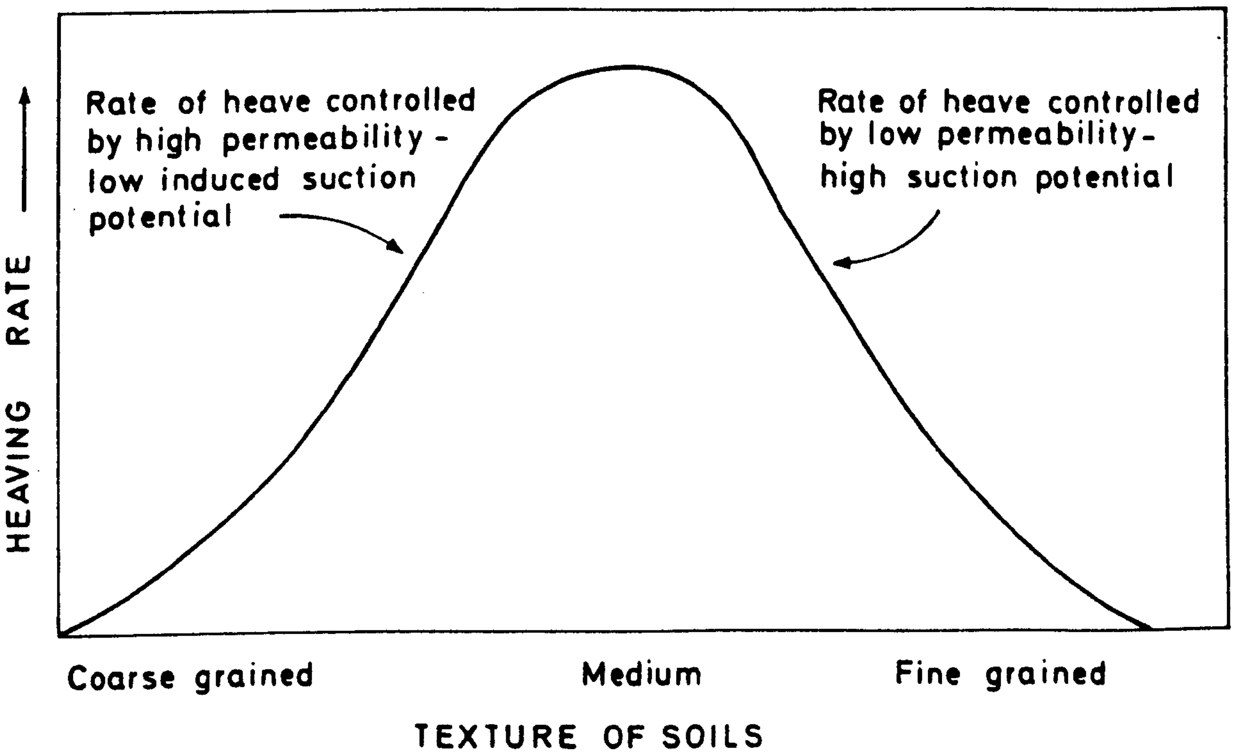

Figure 2.7 : Schematic representation of relationship between heaving rate and particle size resulting from ice lens growth

(Source: Derbyshire *et al.*, 1980; p.208)

Ozawa and Kinosita (1989; p.113) stressed that 'although numerous theoretical studies of frost heaving have been carried out, the problem of why and how the water is drawn toward the freezing front is still debatable. Factors complicating it may be heterogeneity of soils or coupling of water flow and heat flow by the release of latent heat at the freezing front'. Generally, however, it is thought the soil moisture moves to the freezing front in response to a hydraulic gradient. This is comprised of a gravitational component and a soil water potential component. The former is always constant, directed downwards and is independent of the freezing process (Polar Research Board, 1984). The potential gradient, however, is dependent on the freezing process.

Knowledge of the potential (energy status) of soils is therefore important for understanding the movement of water in freezing soils (Polar Research Board, 1984; Williams and Smith, 1989). Thus as well as gravity, forces on soil water include the attraction of soil particles, osmotic effects and the pressure exerted by overlying bodies. These effects determine the total potential of the soil water.

For frost heave and ice segregation to occur there must be a lower potential in the water next to the ice than in the soil moisture below the freezing front. Low potential is caused by low temperatures and/or low moisture contents. The low potential induces the flow of water to the freezing front. The movement of water in the soil is from warm (or wet) to cold (or dry) areas (Biermans *et al.*, 1976). Therefore, soil moisture usually flows in the same direction as the direction of heat transfer (Polar Research Board, 1984).

2.4.3a Rate of moisture flow. The rate at which water is available to a growing needle-ice crystal according to Linell and Kaplar (1959) is a function of:

i) the tension generated within the soil water. Ice formation produces high tension at the freezing front and thus water from the unfrozen area is drawn towards it, resulting in convective heat transfer;

ii) the effective permeability and compressibility of the soil mass below the freezing plane;

iii) the availability of water from the moisture films around individual soil particles. Beskow (1935) believed that the availability of moisture is reduced by overburden pressure which 'squeezes' the waterfilm.

During periods of evaporation the soil-moisture content in the soil profile increases with depth (Outcalt, 1970b). Thus, the soil layer with a high enough water content for ice segregation may be several millimetres below the ground surface. Nucleation may be followed by a period of in-situ freezing, during which the soil moisture is frozen in-situ. Once the freezing front descends to the region of sufficient moisture, ice segregation begins. The frozen soil above the segregation line is pushed up by the ice needles and forms a soil cap (Sections 3.2.2 and 7.3.3).

2.5 CONTINUITY AND DISCONTINUITY OF NEEDLE-ICE GROWTH

To maintain the stability of the freezing front, and hence the growth of clear needle ice following ice segregation, the rate of heat flow away from the freezing front towards the soil surface must be balanced by the heat released when the ice crystallises (known as the latent heat of fusion) and heat that flows to the freezing front from the unfrozen soil below (Figure 2.8) (Fukuda, 1936; Higashi, 1958; Outcalt, 1971a; Sayward, 1979; Meentemeyer and Zippin, 1980). If these conditions are not satisfied, instability results.

An increase in the transfer of heat away from the soil surface can occur when the soil-surface temperature decreases rapidly. This may arise if the sky clears following a cloudy period, causing rapid increases in heat loss by radiation and evaporation. When the rate of heat removal suddenly increases, the soil water freezes more rapidly and increases the water tension immediately below the site of ice nucleation, which, if segregation is to continue, must be balanced by an increased flow of water to the surface. If only limited moisture is available then in-situ freezing of soil water occurs, which produces pore ice, not needle ice. Similarly, Ozawa and Kinosita (1989) found that when the temperature at the freezing front lowered below a particular temperature then ice intruded into the filter on which they grew the segregated ice. The supercooled state below the filter stopped and ice on the filter ceased to grow.

The disturbance of needle-ice growth is thought to be particularly important when studying the geomorphic significance of needle ice because it has been suggested by Fukuda (1936) and Outcalt (1971a), amongst others, that disturbances of the type discussed above result in the incorporation of sediment into the ice crystals (see Chapters 3 and 7 for a detailed discussion). Taber (1929), for example, stated that 'as soon as crystal growth is checked at any point, the temperature of the adjacent soil particle begins to fall, for heat is no longer liberated at this point by the conversion of water into ice; and, since water is a poor conductor of heat and has a higher specific heat than the minerals present in soils, the temperature of the bottom of the soil particle will reach the freezing point sooner than the water with which it is in contact. This helps to bring about the inclusion of the soil particle in the ice'. This sediment later becomes available for transport by needle ice or other processes (Chapter 3). It is perhaps through disturbance to growth, therefore, that needle ice becomes active as an erosional agent.

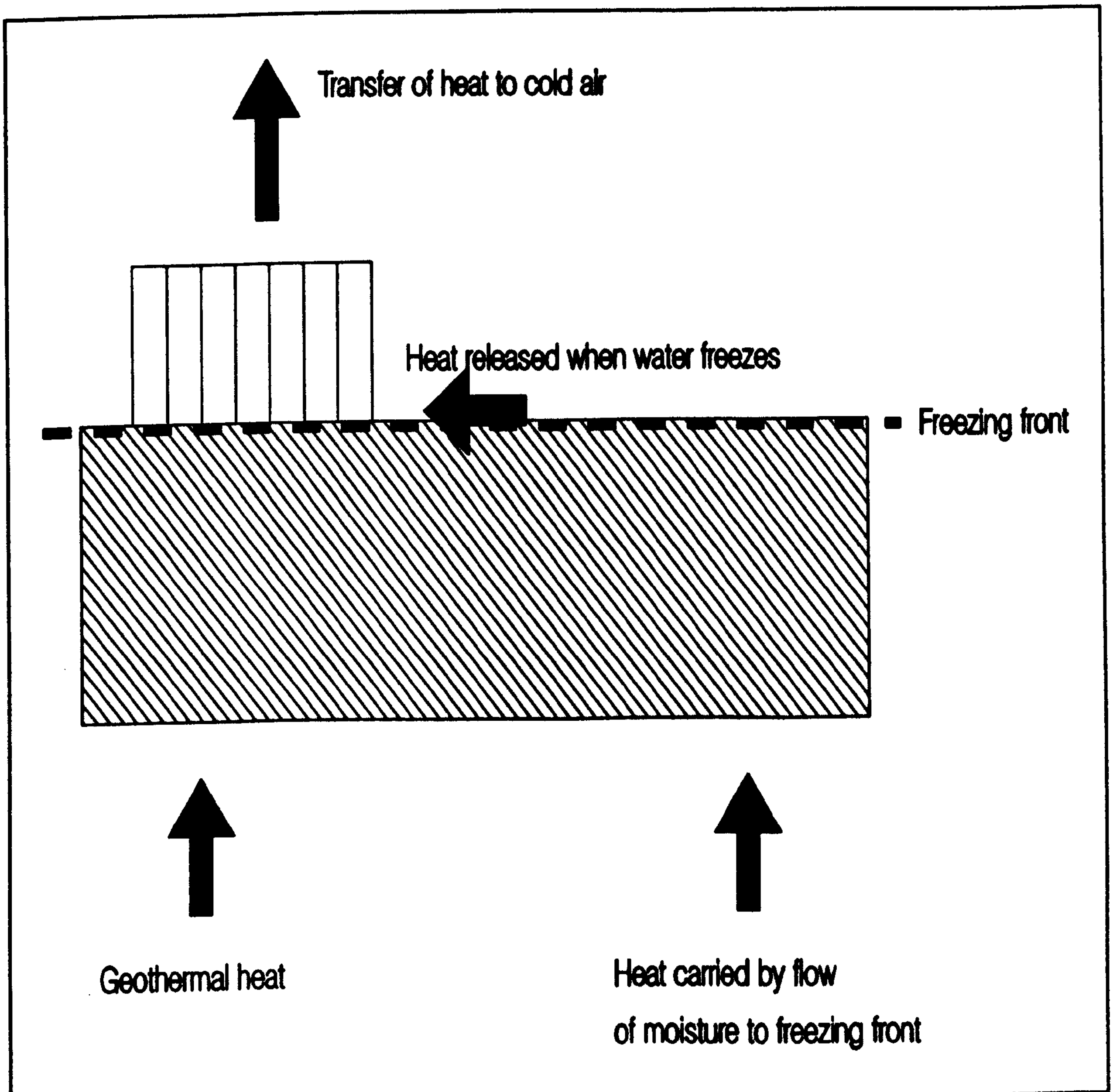

Figure 2.8 : Main sources of heat flow during needle-ice growth.

2.6 CONCLUSIONS

The preceding discussion has shown that there are three main requirements for needle-ice growth (after Outcalt, 1971a):

i) the supercooling of the soil water to the ice nucleation temperature;

ii) a stable freezing front, maintained by the availability of soil moisture and the transfer of heat to and from the soil surface to allow ice segregation;

iii) a sufficiently rapid flow of moisture to the freezing front so that ice segregation continues.

The process of needle-ice growth is complex and is dependent on the coupling of many variables. Thus, variations in meteorological or soil characteristics, along with variations in soil-moisture availability affect the timing of ice nucleation and the amount and rate of needle-ice growth.

It was suggested in Section 2.5 that disturbance to needle-ice growth may result in the incorporation of sediment into the needle-ice crystals, and subsequent downslope transfer of sediment when the needle ice melts. These processes are discussed in the following chapter.

Chapter 3

SOIL EROSION AND TRANSPORT BY NEEDLE ICE : A REVIEW

3.1 INTRODUCTION

This chapter reviews the erosional significance of needle ice and the processes by which it is thought that needle ice can assist in the removal of sediment from a slope or river bank. The factors which determine the extent to which needle ice is an agent of soil erosion are summarised in Figure 3.1.

The significance of needle ice as a disruptive agent in soil has been widely documented. Troll (1958; p.27) suggested that 'the study of needle-ice geography is rightly of increased significance for the mechanics of soil erosion in different frost climates of the earth', whilst Zotov (1940, p.258) stated that 'soil erosion in which the action of frost plays a part is now very widespread on the high ranges [of New Zealand]'. The initial stage of soil erosion here was the exposure of the ground surface, resulting from the depletion of vegetation due to burning, animal trampling or grazing. Following this, needle-ice growth was found to be common on the bare soil, with a subsequent removal of sediment.

A similar link between animal grazing and frost activity was observed in Iceland by Arnalds *et al.* (1987). Severe land degradation was attributed to the complex relationships between livestock grazing, the cold climate and the abundance of frost-susceptible volcanic deposits. Heavy grazing was particularly important as it reduced the resistance of vegetation to hazards such as needle-ice events. Once the land had been denuded revegetation was difficult due to persistent needle-ice formation on the bare soil. Similarly, in north-east Japan Sawaguchi (1987) reported that

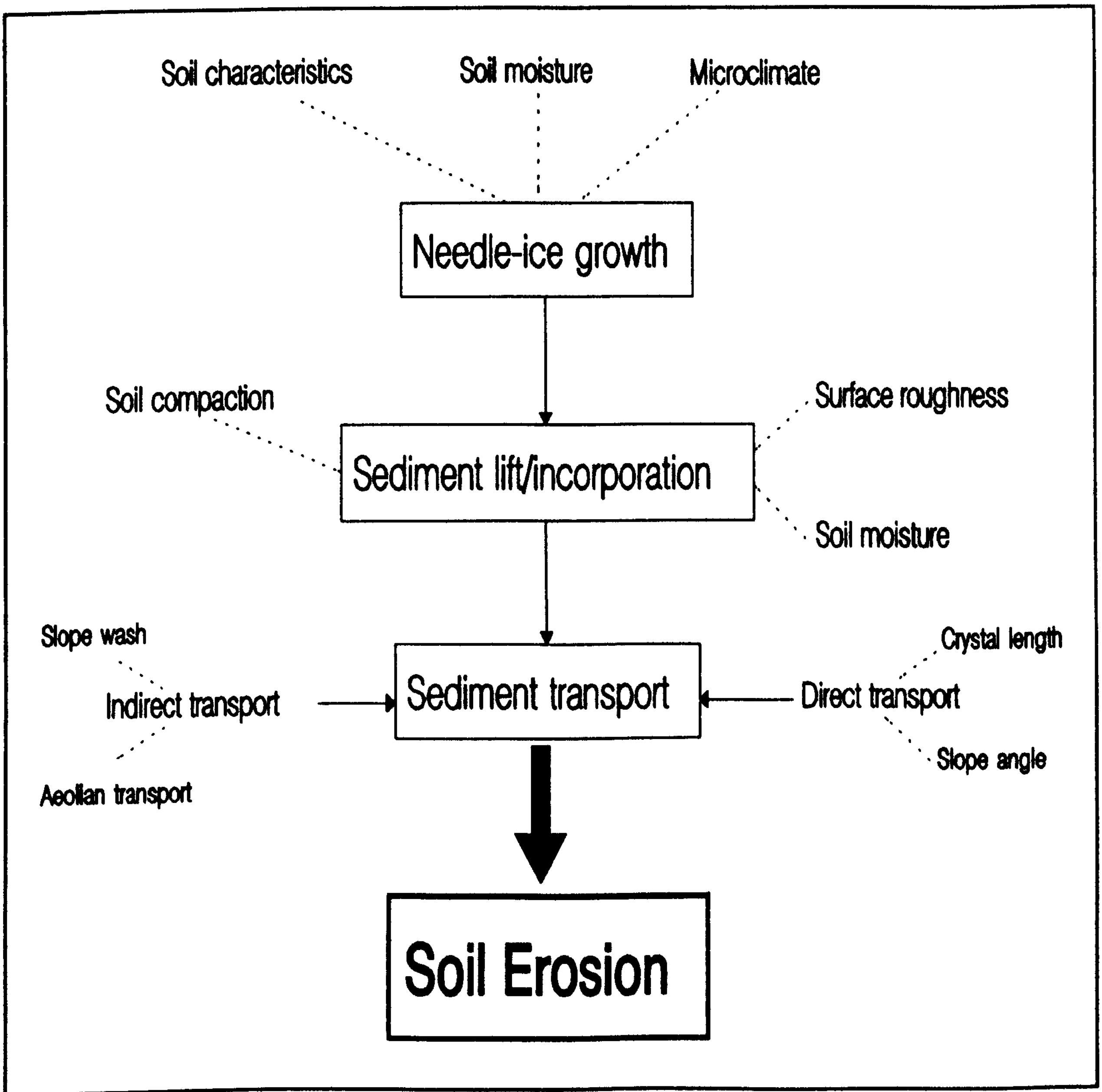

Figure 3.1 : The main factors which determine the efficacy of needle ice as an agent of soil erosion

human disturbance on slopes left the ground bare and thus promoted needle-ice growth. When the needles subsequently melted there was a slow mass movement of material downslope.

In the wooded Birkbaach catchment of the Luxembourg Ardennes (Imeson *et al.*, 1974) the high suspended sediment concentration of the river was attributed to the development of needle ice on the river banks. The sediment of the river-bank material became more erodible as a result of lift by needle ice, and entered the river by rainsplash action. Similar processes are discussed by Hill (1973), Leopold (1973) and Lawler (1986, 1987). The disruption of material by needle ice also makes debris available for aeolian erosion and fallout attachment (Osburn, 1974). Osburn (1974) suggested that loosening of the soil by needle ice makes the repeated resuspension of debris possible.

The erosive effectiveness of needle ice is primarily dependent upon the amount of soil which is initially lifted and incorporated by the needle-ice crystals. The processes which cause this lift and incorporation are described in the following sections.

3.2 LIFT AND INCORPORATION OF SEDIMENT BY NEEDLE ICE

There are two ways by which needle ice removes sediment from the host soil sample: 'lift' and 'incorporation'. Soil lift occurs when the sediment is pushed up on top of the needle ice, whilst soil incorporation occurs when the sediment is included within the ice crystals. The different forms of sediment lift and incorporation result in the formation of different types of ice crystal. In the literature the terminology regarding these different types is confusing and thus the following section attempts to establish a new terminology to describe the characteristics of needle-ice crystals (Table 3.1 and Figure 3.2) based on the location of sediment within the ice and the process by which it was incorporated. This terminology is used throughout the thesis.

Table 3.1 : Needle-ice characteristics

Category	Needle type	Description	Formation discussed in Section
One tier	**Clear**	No sediment	6.1
	Soil cap	Sediment lifted on top of ice crystal. Can be frozen or unfrozen	3.2.2 7.2.3
	Dispersed sediment	Sediment distributed throughout ice crystal	3.2.3 7.2.2
Multitiered	**Polycyclic**	Produced during several freezing cycles	3.2.3
	Monocyclic	Produced during one freezing cycle	3.2.3 7.2.1

3.2.1 Characteristics of needle-ice crystals

The crystals are first distinguished on the basis of whether the needle ice is composed of one tier of crystals or several tiers (Table 3.1 and Figure 3.2). In the 'single tier' category the crystals can be clear (Figure 3.2A), have a soil cap (Figure 3.2B) or contain sediment distributed throughout the crystal (dispersed sediment crystals) (Figure 3.2C). The soil cap can be frozen or unfrozen. Crystals can often have characteristics pertaining to more than one division, e.g. clear crystals with an unfrozen soil cap, dispersed sediment crystals with a frozen soil cap.

In the 'several tier' category (multitiered ice) there are two main divisions, based on how the crystal formed. Thomson (1912; p. 271) defined this type of crystal as 'columns ... arranged in several tiers one tier below another, the lower having been later formed than those above them, and having pushed the older ones up'. Polycyclic multitiered crystals (Figure 3.2D) (after Outcalt, 1970b) (often termed compound crystals in the literature) form during more than one freezing event. They often have a thin layer of clear ice between successive tiers of crystals. Monocyclic multitiered crystals (Figure 3.2E) are formed during one freezing cycle. These crystals usually have a layer of sediment between tiers of ice. Both polycyclic and monocyclic

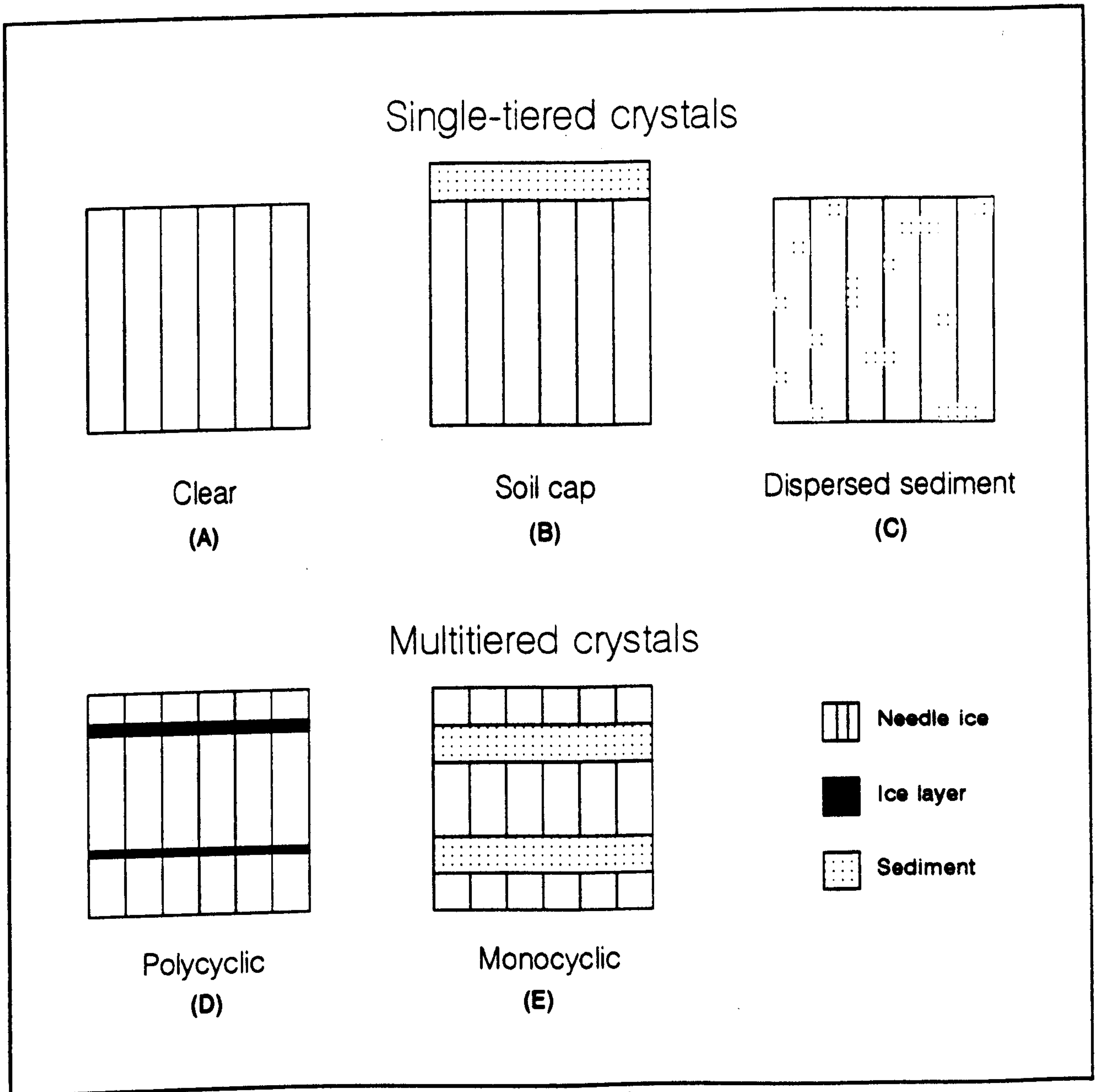

Figure 3.2 : Different types of needle-ice crystal

multitiered crystals can have a soil cap and be composed of clear ice or ice with dispersed sediment e.g. polycyclic multitiered clear ice with a frozen soil cap.

3.2.2 Soil lift

A soil cap is a layer of either frozen or unfrozen soil which is lifted on top of the needle-ice crystals, and is distinct from that which is incorporated within the needle-ice crystals (Section 3.2.3). Tufnell (1971; p.104) stated that 'the existence of debris on top of the ice needles proved that their development contributes to the disturbance and erosion of slopes'.

When the soil surface is 'very wet' needle ice usually forms at the soil surface, and does not carry a sediment cap. If the soil surface is first desiccated by evaporation, however, the freezing front seems to form deeper in the soil and a sediment cap is often lifted on top of the needles (Outcalt, 1971a; Meentemeyer and Zippin, 1980). In this case, the soil-moisture content in the upper soil surface is below the critical level required for ice segregation (Section 7.2.3; Outcalt, 1971a).

The process by which soil caps may form is shown schematically in Figure 3.3. Following ice nucleation there is a period of normal (in-situ) freezing, and a cap of hard frozen soil may be formed (Figure 3.3B). Once a sufficient supply of water is tapped then ice segregation commences beneath the frozen layer and the soil particles above the zone of ice segregation are pushed up by the crystals to form a soil cap (Figure 3.3C).

Soons (1967a) observed that a wide range of material could be lifted by needle ice. Needles less than 1.5 cm long raised fine material, including grit, and tiny pebbles. Stones greater than 5 cm long, however, were not lifted by the ice crystals, and tended to insulate the soil underneath them.

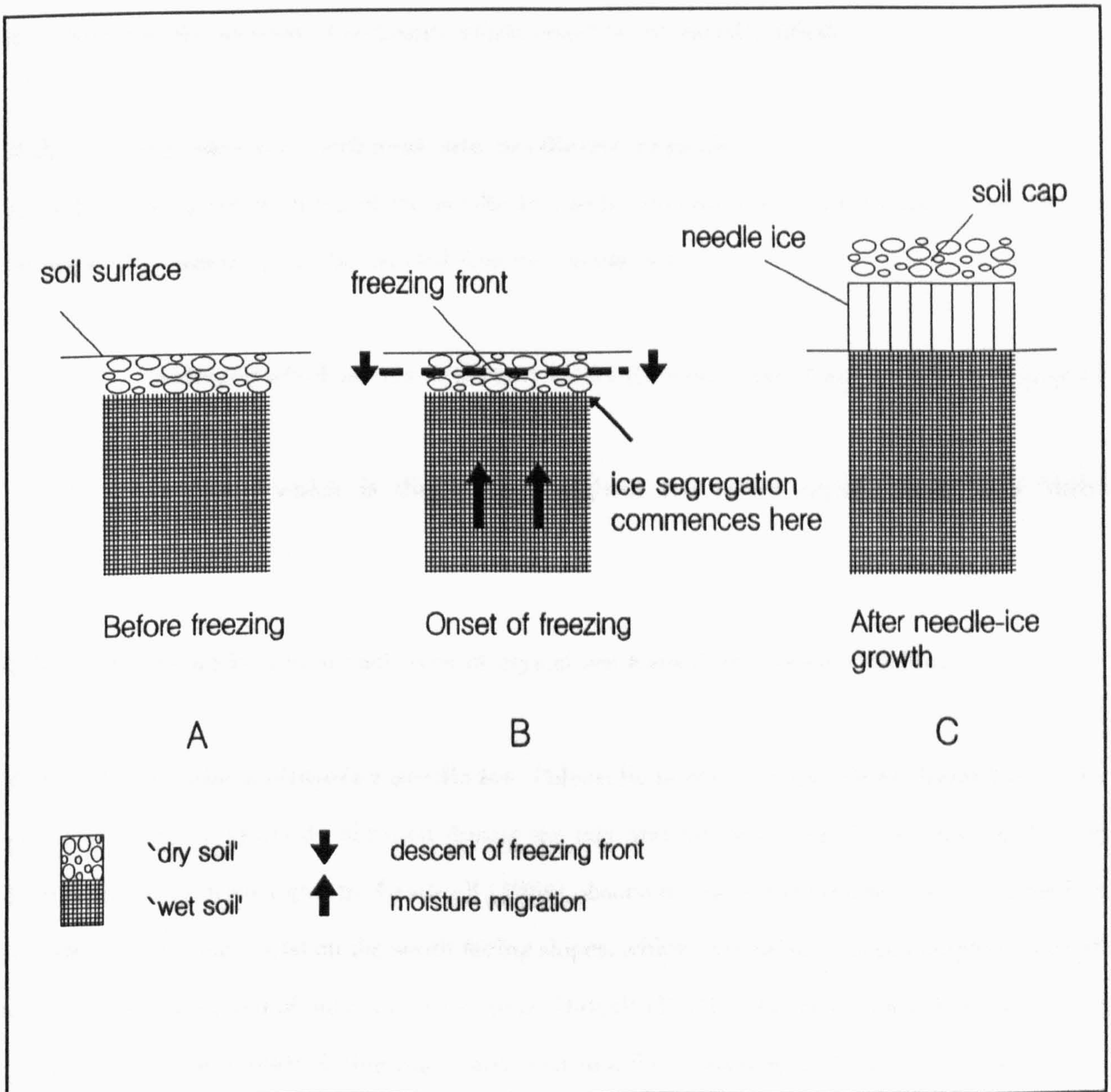

Figure 3.3 : Possible mechanism by which soil caps are formed

The amount of sediment lifted by the ice crystals is probably dependent on the composition, compaction (Yamada *et al.*, 1955; Pérez, 1986 , Soons and Greenland, 1970; Pérez, 1987a) and surface roughness (Soons and Greenland, 1970; Pérez, 1987a; Meentemeyer and Zippin, 1981) of the soil. All these factors control the location at which the freezing front develops in the soil, and therefore the amount of sediment which could be potentially lifted.

3.2.3 Incorporation of sediment into needle-ice crystals

As well as being lifted on top of the needle ice, sediment can also be incorporated into the ice crystals. This material can be divided into two categories:

i) sediment which occurs in distinct layers (between tiers of monocyclic or polycyclic crystals);

ii) sediment which is dispersed throughout the entire crystal giving it a 'dirty' appearance.

The conditions under which each type of crystal are formed are reviewed below.

3.2.3a Polycyclic multitiered needle ice. Polycyclic needle-ice crystals are formed when the previous night's crystals do not melt during the day and the 'old' crystals are thus pushed up by the following night's growth. Gradwell (1954) observed that four-tiered needle ice formed on a north-facing slope whilst on the south-facing slopes, which experienced more complete diurnal thaw, the ice consisted of only one or two tiers. Outcalt (1970b) observed that polycyclic needle ice was formed on a north-facing road bank next to a forest margin, and on a flower bed on the northern side of a wooden fence. Both areas were shaded from direct solar radiation and the needle ice produced one evening did not melt the next day.

3.2.3b Monocyclic multitiered needle ice. This type of crystal is produced during one freezing cycle and sediment is often incorporated as distinct layers into the needle ice. It is postulated by Fukuda (1936), Hay (1936) and Outcalt (1971a) that each layer represents a temporary descent of the freezing front. The freezing front is considered to descend as a result of unsteady heat and moisture conditions in the soil. Soons and Greenland (1970) suggested that the development of multitiered needle ice is a function of the position and movement of the freezing front, the availability of soil moisture and the amount of heat released by the change of moisture into ice. The factors are controlled by the flow of heat in the soil sample. Within a frozen soil system there are four main sources of heat (Chapter 2):

i) solar and terrestrial radiation receipts;

ii) heat released when water freezes - i.e. the latent heat of crystallisation;

iii) heat conducted across the temperature gradient between the warmer subsurface soil and the surface layer;

iv) heat transferred by the flow of water to the freezing front.

If more heat is removed from the surface than is received at the freezing front then the soil surface temperature decreases rapidly (as long as the moisture content of the soil does not change appreciably). It is thought that heat can be made available to compensate for this by either lowering the soil temperature or freezing more water. Whilst there is sufficient water available, the freezing front remains stationary and needle ice continues to grow (Section 2.5). If the water supply is limited, however, the soil temperature can be lowered, the freezing front may then descend, and soil water is frozen in-situ. When a further supply of moisture is 'tapped' needle-ice growth probably recommences and the frozen sediment then forms a layer between the 'older' and 'newer' needle-ice crystals.

3.2.3c Crystals with dispersed sediment. Outcalt (1971a) suggested that needles which contained dispersed sediment are formed when areas of ice segregation are separated by areas of in-situ freezing. This is caused when soil moisture within the soil is limited and occurs over very small areas (probably in the order of only several soil pores). Outcalt determined that dirty needles are formed during the transition from clear growth to in-situ freezing. This is discussed further in Section 7.2.2.

3.2.4 The amount of sediment lifted/incorporated.

'Apparently little information is available on the quantities of soil lifted ..., perhaps because it is a tedious task' (Meentemeyer and Zippin, 1980; p.37). Table 3.2, however, shows the amounts of sediment which were lifted and incorporated by needle ice in previous studies.

The variation in the amount of sediment lifted by the needle ice (Table 3.2) is probably a result of differences in the intensity, cover, length and type of needle ice and in the compaction, soil-moisture content and slope of the soil (e.g. Section 3.2.2).

3.2.5 The needle ice algorithm of Outcalt

Outcalt (1971a) devised an algorithm to describe needle-ice growth and the frozen soil structures that are produced during growth (Figure 3.4). This model attempts to explain what occurs when the continuity of needle-ice growth is disturbed (Section 2.5).

Using the algorithm Outcalt (1971a) examined the development of six micro-morphologic soil structures. These included a soil cap, clear needles frozen and unfrozen at the base, and dirty needles. These structures were expected to form as a result of various limiting conditions and interruptions which may occur during needle-ice growth. For example, ice segregation is often limited and occurs in a spatially and temporally heterogenous manner. Needle-ice growth occurs at points where the soil texture and moisture conditions are favourable and is thus discontinuous,

Table 3.2 : The amounts of sediment lifted and incorporated by needle ice

Author	Location	Sediment uplifted ($g\ cm^{-2}$)
Steinemann (1955)	Weissfluchjoch, Germany	5
Yamada *et al.* (1955)	Japan	0.4[a] 0.8[b]
De la Rue (1959)	Iles de Kerguelen	0.939 1.350
Brink *et al.* (1967)	S.W. British Columbia, Canada	0.01 - 1.0
Schmid (1955)	Black Forest, Germany	0.065 - 7.2
Meentemeyer and Zippin (1980)	Georgian Piedmont, U.S.A.	0.85[c] 1.05[d] 1.12[e]
Meentemeyer and Zippin (1981)	Laboratory	0.0 - 1.9
Lawler (1984)	South Wales, U.K.	0.002 - 0.402
Pérez (1986)	Venezuelan Andes, Venezuela	0.58[a] 2.36[b]
Present study	Laboratory	0.002 - 2.5

[a]'compact' soil
[b]'loose' soil
[c]16° slope
[d]21° slope
[e]38° slope

(Adapted from Lawler, 1984; p.263)

soil may therefore become incorporated into the ice crystals. If ice intrusion is spatially homogeneous, however, frozen soil is produced. The structures described in the algorithm, and the conditions under which they are produced, are summarised in Table 3.3.

3.3 TRANSPORT OF MATERIAL BY NEEDLE ICE

The transport of material by needle ice is significant for the processes of soil creep, frost sorting, the differential movement of material downslope and the formation of several types of patterned

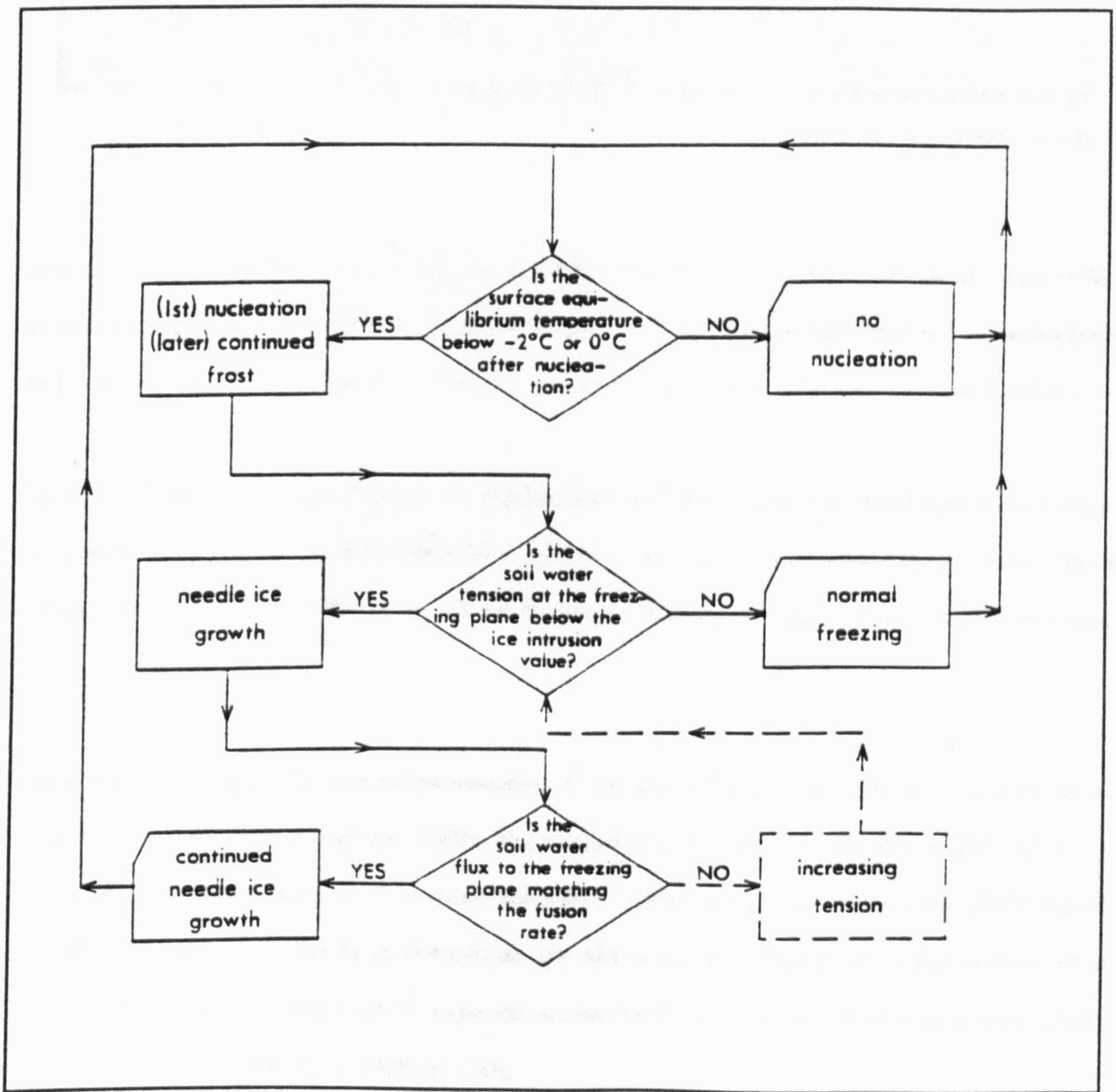

Figure 3.4 : The needle ice algorithm of Outcalt (1971a)

Table 3.3 : The conditions under which different types of needle ice and frozen soil are formed

Type	Class of ice segregation		Post-nucleation environment
	In space	In time	
Clear needles	Homogeneous	Continuous	Limiting only cap base
Dirty needles	Homogeneous	Discontinuous	Intermittently freezing
Hard frozen	None	Continuous	Continuously limiting

Source : Outcalt (1969; p.1381)

ground. Mackay and Mathews (1974b), for example, measured the surface movements of particles in south-west British Columbia over a ten year period. They showed that frost heave, snowcreep and surface wash were unimportant relative to needle ice in the formation of sorted stripes.

Davison (1889) was perhaps the first to suggest that frost heave and thaw produced a downslope movement of particles on hillslopes. He observed that in most circumstances heave lifted material perpendicular to the slope, whilst the thaw component deposited the uplifted material vertically (Section 3.3.1).

Since Davison's paper the downslope transfer of material by needle ice has been described by a number of authors (e.g. Czeppe, 1968; Meentemeyer and Zippin, 1980; Pérez, 1987a,b,c). A variety of terms have been used in these accounts, 'creep' being used most often. With regard to soil movement creep has been defined as 'the net downward displacement that occurs when the soil, during a freeze-thaw cycle, expands normal to the surface and settles in a more nearly vertical direction' (Benedict, 1970; p.170).

The extent to which needle ice can move material is still uncertain. Pérez (1987c; p.34), for example, stated that 'only a shallow soil layer and those stones on, or slightly beneath, the ground surface are disturbed by needle ice activity'. Mackay and Mathews (1974b) also determined that sediment movement initiated by needle ice decreased rapidly with depth, and was almost zero at 7 cm below the surface. Some authors (e.g. Troll, 1958; Soons, 1967a; Mackay and Mathews, 1974b) have reported that needle ice can transport stones greater than 30 cm long and 10-15 kg in weight. Others (e.g. Rapp, 1970; Price, 1981), however, suggest that it is incapable of moving material greater than 5-10 cm in length.

Table 3.4 shows a summary of rates of needle-ice induced transport from previous studies. It is not possible to standardise these results to have the same time span because of differences in the number of needle-ice events per year, both between locations and in different years in one location.

The rate of particle transport is controlled by a number of other variables as well as needle-ice frequency. Slope angle is an important factor for determining the distance transported, regardless of the mechanism of transport. Brockie (1968), for example, found that on low gradients (c.2°) the needle ice collapsed randomly, and adjacent bundles of needles fell in different directions. For there to be any consistent downhill movement he argued that there had to be far steeper slopes.

Pérez (1987b) investigated the effects of soil compaction on the rate of needle-ice induced particle transport in the Venezuelan páramo by artificially compacting one plot and leaving an adjacent plot undisturbed. On the compacted plot the length of needle ice was reduced by 40% to 50%, thus the amount of sediment movement by gravity fall (see below) was expected to be reduced. Particle tumbling, however, was increased as the smooth, uniform surface provided minimal resistance to downslope movement.

Pérez (1987b) stated that differences in particle movement can also be a result of variations in soil-moisture content, aspect, gradient and soil depth, all of which influence needle-ice growth.

Table 3.4 : Rates of sediment transport by needle ice on hillslopes

Author	Location	Marker	Slope (°)	Rate
Gerlach (1959)	Tatra Mountains, Poland	Rock debris	16 - 33	350-400 mm a^{-1}
Ellenberg (1955)	Kanto plain, Japan	3 different native clasts	N.S.	22 mm, 27 mm, 90 mm in 5 days
Gradwell (1957)	South Island, New Zealand	Clasts, 20-70 mm diameter	11	630.5 mm a^{-1} (maximum)
Smith (1960)	South Georgia	Clasts	21	360 mm in 6 days
Hayward and Barton (1969)	New Zealand	Painted clasts	22	1-3.5 feet in 22 events
Benedict (1970)	Colorado Front Range, U.S.A.		N.S.	4 - 43 mm a^{-1}
Higashi and Corte (1971)	Laboratory	Marbles	3 15	5-10 mm in 3 cycles 30 mm in 3 cycles
Zhigarev (from Czudek and Demek, 1972)	East Siberia, U.S.S.R.	Clasts	N.S.	140 - 180 mm in 36 days
Mackay and Mathews (1974b)	Cinder Cone, U.S.A.	Fine particles Marbles		150 mm a^{-1} 350 mm a^{-1}
Meentemeyer and Zippin (1980)	Georgian Piedmont, U.S.A.	Soil particles	16 21 38	14 mm/event 15.7 mm/event 22.5 mm/event
Walton and Heilbronn (1983)	South Georgia, Falkland Islands	Clast 70 mm long	20	60 mm a^{-1}
Pérez (1987)	Venezuela	Clasts <40 mm		229 mm a^{-1}
Sawaguchi (1987)	Japan	Clasts		110 mm/event 80 mm/event

N.S. : not stated

Walton and Heilbronn (1983) found that the most pronounced downslope movement of clasts was on east facing slopes, and these experienced the most intense needle-ice growth. The distance that individual clasts moved was negatively related to clast size and positively related to altitude.

Sediment transport caused by needle-ice growth can either be direct or indirect. The former implies that material is removed from the slope or river bank purely as a result of needle-ice heave. Needle ice is an indirect agent of soil erosion when it prepares the soil for removal by a secondary agent such as runoff.

3.3.1 Direct transfer of sediment by needle ice

Several processes have been described to represent the way in which needle ice transports sediment directly downslope. These are outlined below and shown schematically in Figure 3.5.

3.3.1a Direct, vertical dropping of material. This is the classic gravity-fall, soil-creep or vertical settling model of soil transport as defined by Davison (1889). Material is uplifted normal to the soil surface during freezing and then deposited vertically on melting. The distance that material is transported can be calculated using the equation

$$d = h \tan S \tag{3.1}$$

where d is the downslope component of movement, h is the amount of heave normal to the surface due to frost action and S the slope angle.

The above model, however, is based on the following assumptions, which, in a field setting, are not likely to be met (after Lawler, 1984):

i) needle ice grows perpendicular to the growth medium;

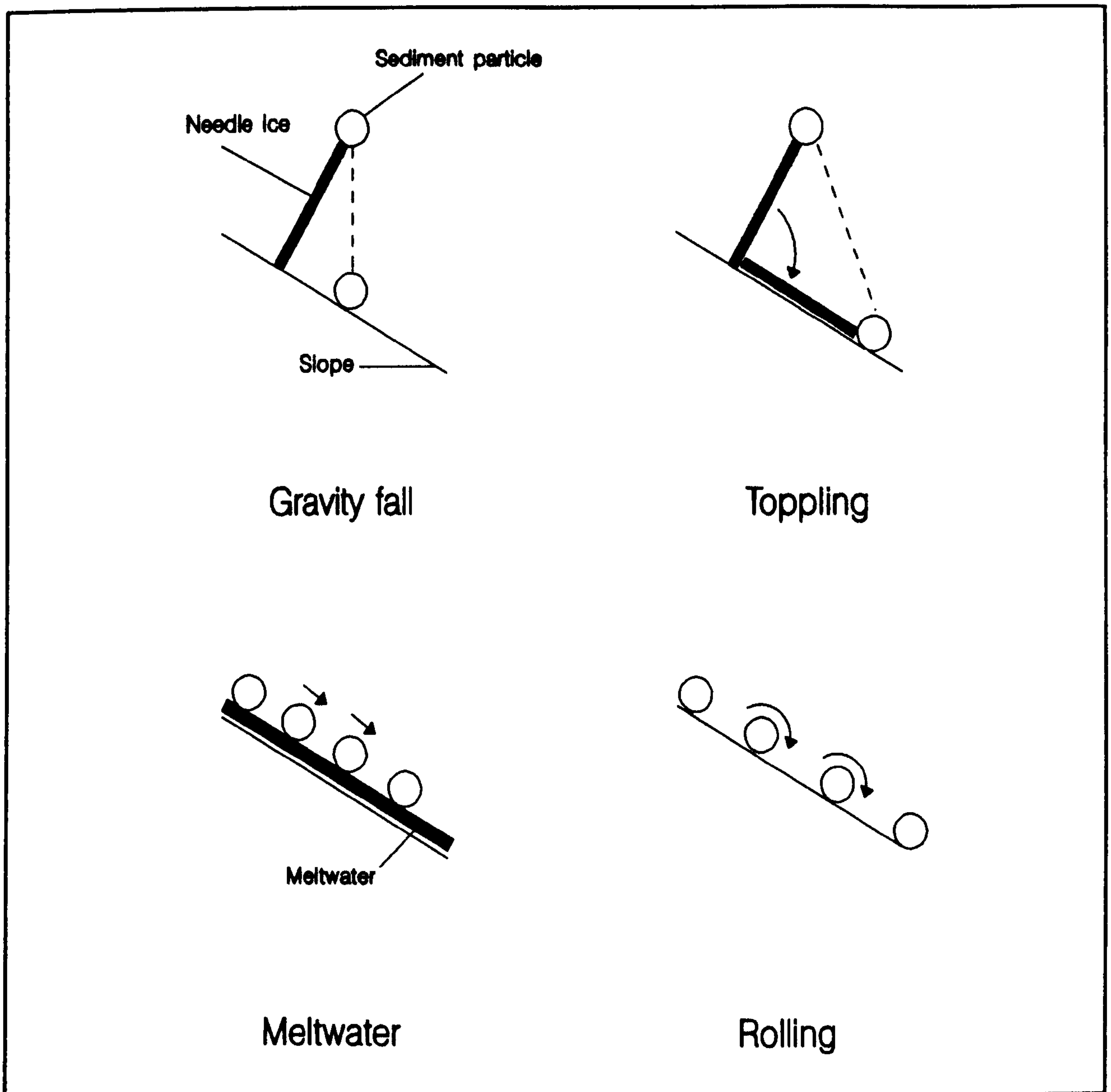

Figure 3.5 : The mechanisms by which needle ice transports sediment downslope

ii) material drops vertically when the ice melts;

iii) the particle does not move once it is deposited onto the slope;

iv) the needle-ice crystals are straight.

Higashi and Corte (1971) produced a modified version of the traditional gravity-fall equation in an attempt to make it more representative of the actual process, recognising that material does not drop vertically. They suggested that particle movement at the soil surface and down to 200 mm below the soil surface can be represented by

$$d = h\ (\tan S)^2 \tag{3.2}$$

The use of the squared tangent of the angle is intended to represent the ice crystals bending downslope whilst melting. In addition to transfer by gravity fall, Higashi and Corte (1971) suggested that sediment was moved due to the slip or rotation of particles. This occurred as a result of the loss of adhesion between sediment particles and the ice (which is sensitive to temperature). Slip and rotation were thought to occur as the ice crystals melt, and in the saturated soil after melt is completed. The latter form of movement is termed gelifluction (see below).

It can be argued, however, that neither of these models can be directly applied to field observations because:

i) the angle of the radiation receipts influences crystal thaw;

ii) many particles keep moving once they fall onto the ground.

The gravity-fall models thus appear to be an oversimplification of the process of needle-ice transport. Mackay and Mathews (1974b; p.355) argued that the gravity-fall equations are not directly applicable to movement induced by needle ice in field conditions where the sun angle is often important in influencing crystal thaw. They stated that 'observations show that gravity settling is an exception, not the rule'. Other needle-ice transport mechanisms have been described, and are outlined below.

3.3.1b Toppling of small bunches of needle ice. As needle-ice crystals melt the weight of the sediment cap on top of the needles causes them to be unstable and the crystals collapse 'domino style' (Lawler, 1984; p.266). Meentemeyer and Zippin (1980) suggested that most downslope transfer is caused by the ice crystals tumbling followed by an undetermined length of slide by the debris. Such movement was observed on the steep slopes of gullies, roadcuts and construction sites.

Mackay and Mathews (1974b) also suggested that ice needles topple downslope like matchsticks along with their debris cap. From field data they showed that the mean annual movement of the soil surface was 31 cm a^{-1}. If this movement resulted from gravity fall then a total growth of 115 cm a^{-1} of needle ice would be required for the given slope angle, which was thought to be excessive in a single season. If the needle-ice crystals toppled, however, then only 31 cm a^{-1} of growth would be required. It was thus suggested that the displacement of soil particles by crystal toppling should be represented by

$$d = h \tag{3.3}$$

3.3.1c Transport in meltwater. Sediment has been observed to be transported in the meltwater produced by melting crystals. Lawler (1984; p.266) observed 'sediment-laden rivulets of meltwater' flowing across sheets of needle ice, and at the needle-ice/bank interface. This mechanism was expected to occur during the early stages of needle-ice melt.

A similar process was reported by Rayner (Pers. Comm. to Soons, 1967a; p.221), although it was thought to occur later in the melt process than postulated by Lawler. Rayner called this process 'material slump' and stated that it occurred when melt converted the soil surface into a slippery mud. It was suggested that fine material would move a greater distance than determined in calculations such as the gravity-fall model.

The release of large amounts of water during needle-ice melt can also give rise to gelifluction. Higashi and Corte (1971) stated that the amount of particle movement is determined by the time that the excess water remains in the soil. They suggested that the total movement (solifluction) caused by needle ice can be calculated by summing the distances moved as a result of frost creep and gelifluction.

3.3.1d Rolling and free-fall of particles. When stones fall onto a steep slope they are likely to roll downslope. The importance of this type of transport is determined by the characteristics of the particles themselves. Smooth, well rounded pebbles of high sphericity should roll a greater distance than flat pebbles or soil aggregates.

Harvey (1974; p.50) observed the free-fall of particles individually loosened from the till sides of Grains Gill. He stated that 'during thaw, after heavy frost, there may be a continuous rain of small stones and boulders from the gully slopes'. Smith (1960) reported that one particle moved 360 mm in six days. This was thought to have occurred after thawing released the particle from a position of instability.

3.3.1e Horizontal movement. In a study of patterned ground in East Otago, New Zealand, Brockie (1968) recognised three different types of particle movement caused by needle ice:

i) horizontal rotation around the shortest axis. All stones rotated, often randomly, Brockie suggested that this is indicative of needle-ice development;

ii) horizontal displacement. This was usually erratic but some stones showed movement in a particular direction. The mean horizontal movement in 18 months was 42 mm (min 0 mm, max 75 mm);

iii) movement which depended on the stage of development of the patterned ground. The stones moved laterally and as they were incorporated into developing gravel bands they rotated around the a- or b-axis so that they lay on their edge. This process was thought not to be attributed wholly to needle-ice growth, however.

3.3.2 Indirect transport of sediment by needle ice

On some occasions when the needle-ice crystals melt, the lifted soil is deposited with little or no direct sediment transport. When this occurs needle ice can be an agent of sediment preparation rather than sediment transport. Soons (1971; p.468), for example, argued that 'even where needle ice does not directly cause movement of soil downslope, the part it plays in preparing the soil for removal by other agents is important'. The lift and deposition of sediment alters the structure of the soil and often increases the erodibility of the sediment. These changes are reviewed below.

3.3.2a Changes in the soil structure caused by needle ice. Needle-ice development can affect soil structure by heaving the soil and changing soil-moisture content. When both the soil cap and the underlying crystals melt, the surface settles back irregularly, and the ground may be covered in a puffy/friable layer (Section 4.3.1; Soons and Greenland, 1970). Inter-particle cohesion is often weakened by a sequence of needle-ice events.

Soil structure is affected on both a diurnal and seasonal timescale by needle-ice growth. In the former, ice is accumulated in the surface layer and reduces the bulk density of the soil. Soil lifted by needle ice also has an increased porosity, which increases its infiltration capacity, and consequently decreases the amount of surface runoff measured from a plot affected by needle-ice growth (Soons, 1967a, 1967b; Pérez, 1987a).

In a study in New Zealand of the longer-term effects of needle-ice growth, Gradwell (1954) determined that the amount and persistence of soil fragments on the soil surface following needle-ice growth and melt was controlled by the amount of needle ice produced during the winter and the quantity of moisture available to break up the soil aggregates and merge them into the soil surface. Where drainage was poor, muddy soils were produced by melting needle-ice crystals. Fragments were 'puddled' and dried out, and produced a smooth surface. In well drained areas, soil crumbs produced by needle ice remained for up to a month following the thaw.

3.3.2b Effects of a change in soil structure. The particles loosened by needle ice may be dried out during the day and thus become highly susceptible to aeolian and fluvial removal. Gradwell (1954) stated that soils affected by needle ice were more susceptible to rainsplash. Washburn (1979) also noted that loosely-structured soils favour needle-ice growth, and repeated growth loosens the soil.

In many areas, large amounts of bank erosion have been associated with relatively frequent discharge events (at or below bankfull), which follow periods of subaerial preparation, particularly needle-ice growth. In such an instance, needle ice, by enlarging joints in the bank (Hill, 1973; Knighton, 1977) and producing a loosely consolidated skin (Knighton, 1977; Gardiner, 1983), increases the susceptibility of the bank material to erosion. This susceptibility is exploited by subsequent flows which may remove the prepared material.

Lawler (1984) estimated that the direct erosional effect of needle ice on the banks of the River Ilston accounted for only 9% of total bank retreat. It was thus concluded that the direct affect of needle ice as an agent of transport was limited, and that its indirect impact was more important. This involved two stages:

i) following needle-ice growth the majority of sediment was replaced on the river bank. This material had a puffy, friable appearance and was highly susceptible to removal by fluvial action;

ii) when the water level of the river increased, the material was removed from the bank, forming an 'erosional notch'.'The depth of the incision increased in relation to needle ice intensity' (p.270).

Erosion of banks unprepared by frost action was found to be limited. Lawler (1986; p.227) stated that 'although fluvial or hydrological factors seem to control the area of bank eroded ... the amount or intensity of erosion is largely determined by previous cryergic activity'.

Gardiner (1983; p.236) stated that 'the strong association between erosion, frost and hydrological parameters ... would suggest that both frost and fluvial factors are important in promoting the removal of material'. Evidence to substantiate this statement was provided by higher suspended sediment concentrations of the River Lagan, Northern Ireland, following needle-ice growth.

3.4 CONCLUSIONS

The role and impact of needle-ice development on a particular soil is largely dependent upon the characteristics of the area which is being considered. Climate and soil properties control the frequency of needle-ice growth (as discussed in Chapter 2). Other factors, however, such as soil composition and compaction, and length and cover of needle ice may influence the role and importance of needle ice as an agent of landscape change.

In many instances the role of needle ice is dependent upon slope angle. A flat or gently sloping area is not likely to experience much direct downslope transfer, and needle ice is likely to be more important as a preparatory agent. Through lifting by needle ice the soil surface is heaved and disrupted, and can become desiccated. It is therefore susceptible to removal by secondary agents (e.g. aeolian processes, surface wash).

On steeper slopes, however, needle ice is more significant as an agent of direct sediment transport, by the mechanisms of gravity fall, tumbling, sliding and rolling. In such circumstances the preparatory role is of secondary importance, although the soil is loosened ready for transport.

The magnitude and frequency of the needle-ice events and the disturbance to growth will probably determine the effectiveness of sediment erosion by needle ice versus other landforming agents such as mass movement, rainsplash. Taking into consideration needle-ice frequencies (Table 1.2) it is immediately evident (if all other factors are equal) that where events are infrequent the impact of needle ice will be unimportant relative to those areas which experience frequent needle-ice events. Soons (1967a) for example, stressed the importance of needle-ice development in the erosion of mountain areas of New Zealand. Where, although infrequent, localised events such as mudflows or severe stream erosion remove more material than needle-ice events, the importance of the latter lies in their persistence.

Considering the uncertainty of many aspects of needle-ice growth and soil erosion by needle ice, many authors have opted to simulate the growth of needle ice in the laboratory to allow maximum control over the growth environment. These laboratory experiments are described in Chapter 4.

Chapter 4

A REVIEW OF PREVIOUS LABORATORY SIMULATIONS OF NEEDLE ICE

4.1 INTRODUCTION

The present study investigates the growth of needle ice and the transport of sediment by needle ice using a series of laboratory experiments (Chapter 5). Section 4.2 briefly discusses the rationale behind the use of experiments for addressing problems in geomorphology and describes the problems associated with the use of hardware models. The laboratory simulation of freeze-thaw action is then discussed. Following this, case studies of papers which have investigated needle-ice growth and sediment transport are presented. The conclusions are then presented.

4.2 EXPERIMENTAL GEOMORPHOLOGY

4.2.1 Introduction

'Experimental geomorphology is the branch of geomorphology which reveals relationships and regularities between landforms, geomorphic processes and the materials involved in the processes on the basis of laboratory or field measurements under controlled conditions and finally delimits the scope of validity for these relationships and regularities' (Kértesz, 1985; p.21).

In experimental geomorphology, hardware models are often used as part of the investigations. 'Hardware modelling in geomorphology may be defined as the study, under closely monitored or controlled experimental conditions, of a physical representation of a selected geomorphic feature' (Mosley and Zimpfer, 1978; p.439). A significant contribution to the understanding of landforms and landforming processes has been made through the use of laboratory experiments, e.g., rock weathering (McGreevy, 1985; Sperling and Cooke, 1985), frost action (Fahey, 1983; Coutard and Mucher, 1985; Jerwood *et al.*, 1990a, b), sediment transport by rivers (Southard and Boguchwal, 1980), and rainsplash action (Morgan, 1983; Epema and Riezebos, 1984).

The rationale behind hardware models is that the physical processes being studied should be identical to those experienced under natural conditions. Their advantage over field study is that the parameters being considered can be closely controlled and precisely measured, possibly making it easier to identify controlling factors. Yoxall (1983) suggested that it is difficult to comprehend the complexity of reality until the real world is reduced to simplified terms and the essential parameters are abstracted, and hardware modelling makes this possible.

During the last decade there have been many laboratory-based geomorphological studies carried out. This, states Richards, (1990; p.195) is a result of 'a shift from extensive to intensive research designs, and is characteristic of the uncovering of 'ontological depth' emphasised by realist philosophers of science and its methods'. In this context the objective of science is the development of explanations 'based on the identification of networks of underlying causal mechanisms' (Richards, 1990; p.195).

The main problems of hardware modelling as identified by Mosley and Zimpfer (1978) are outlined below. In Chapter 5 these problems are assessed with reference to the experimental design of the present study.

i) initial and boundary conditions may not closely represent natural conditions, or they may influence model behaviour;

ii) materials and processes may not replicate those in nature;

iii) the study of only one or two processes may prevent the observation of interactions that occur in nature. Richards (1990; p.195) also noted this problem, and states that although it can be argued 'that experimentation is necessary to control all but one factor', this approach may not reveal anything about the interactions between them and phenomena in an open system. It is therefore suggested that criteria are required to justify the adherence of an experimental methodology to particular theories. The criteria should be based, in part, with 'the consistency of its [the theory's] explanations with evidence relating to the same phenomena at other time and space scales, and not to other, related phenomena at comparable scales.' (Richards, 1990; p.196);

iv) whilst precision is gained, accuracy of representation may be lost as the model scale decreases;

v) hardware models may be time-consuming and expensive to operate;

vi) they cannot be easily stored;

vii) they cannot be the final stage in the development of a theory.

Despite these problems many studies of freeze-thaw action have found advantages in the use of laboratory experiments. These advantages and two approaches used in these studies are described in the next section.

4.2.2 The laboratory simulation of freeze-thaw action

Higashi and Corte (1972) outlined three advantages of the laboratory simulation of soil freezing and thawing:

i) the time required to reach the affect is shortened;

ii) the scale of the investigation is smaller;

iii) particular experiments can be designed to separate various factors affecting the phenomena.

The study of frost action in the laboratory can be approached in two ways (Penner, 1957). The first method aims to subject soil samples to similar conditions to those that occur in nature. This approach is predominantly used for engineering applications to determine the performance of particular soils under various freezing regimes. The disadvantage of such methods, however, 'is that the simulation in the laboratory of the complex natural field conditions is at best an approximation' (Penner, 1957; p.235).

The second approach recognises that field conditions cannot be reproduced exactly in the laboratory. Attention is thus focused on a small aspect of the frost-heaving process and an attempt is made to control as many variables as possible. Such methods usually aim to isolate the most important factors which influence the effects of the frost action. Higashi (1958) suggested that the misconceptions made regarding frost heaving result from unsuitable test procedures. He stressed that it is important to simulate natural conditions, whilst eliminating factors that are thought to be of minor importance.

4.3 PREVIOUS LABORATORY SIMULATIONS OF NEEDLE ICE

A number of authors have attempted to grow needle ice under laboratory conditions. The main constituents of most previous studies are outlined in Table 4.1. In these experiments soil samples were studied under controlled conditions in the laboratory. It was often assumed that the physical processes operating in the block of soil were identical to those that occur under natural conditions, whilst aspects of the freezing process are closely controlled. Thus, the laboratory simulation of needle ice encompasses both of the approaches described by Penner (1957).

Three case studies are described below to illustrate the principal components of the experiments summarised in Table 4.1.

Table 4.1 : Summary of literature which discuss laboratory experiments of needle ice

Source	Soil type	Temperature control	Moisture supply	Comments
Coblentz (1914)	Used plant stems	Natural cooling (plants put on a window sill)	Continuous	Compared different plants. Found needle ice formation was largely controlled by the existence of sap tubes.
Taber (1918)	Clay and sand	N.S.	Saturated once	Weights put on material which was then lifted by needle ice. Weights on the sand material were not lifted.
Nakaya and Magono(1944)	Hokkaido soil	Constant	Continuous	Amount of heaving was proportional to excessive water drawn from below by capillary action.
Steinemann (1955)	N.A.	N.A.	N.A.	Experiment to determine the optical axis of needle ice. Found that the preferred direction of the optical axis is perpendicular to direction of growth, and therefore the temperature gradient.
Kinbacher and Laude (1955)	Various loams	Constant -7 to -1 °C	Continuous, used wicks	Experiment to investigate seedling heaving. Soil cores allowed to dry between cycles produced less heave than those continuously wet.
Higashi (1958)	Silt from till deposit. Sieved to remove >1 mm	Temperature decreased in steps to -35°C	Continuous, used wicks	To determine the effects of the soil temperature regime on the type of ice segregation.
Horiguchi (1967)		Constant	Continuous, used wicks	Observations of needle-ice growth with a cine camera. No ice grown on smooth soil surface.
Soons and Greenland (1970)	Chiltern Valley soil.Top soil and subsoil reconstructed to resemble original soil profile.	Cooled to -4°C, remained there for 3 days.	Saturated once. Measured with gypsum blocks.	Evaporation and humidity measured. Realistic crystals could not be grown on more than four occasions (due to reduced moisture).

Source	Soil type	Temperature control	Moisture supply	Comments
Higashi and Corte (1971)	Frost susceptible silt clay sieved from volcanic ash and pumice.	Manually lowered 2-5°C d^{-1}	Continuous. Used wicks and waterbath.	Experiment to demonstrate solifluction. Glass marbles used as markers on 3° and 5° slopes.
Van Steijn (1977)	Loess, uniformly distributed.	Lowered from 15°C to -12°C in 32 hours.	Saturated once. Measured with nylon elements.	Creep measured using plastic needles, position related to grid system. Discussed possibility of continuous monitoring of moisture.
Meentemeyer and Zippin (1981)	Sandy loam.	Constant	Saturated once.	Needle ice allowed to melt back into the soil following each experiment, but did not form the dry crust as expected in nature.
Ozawa and Kinosita (1989)	Microporous filter used as a medium. Pore sizes 0.015μm - 0.2μm.	Cooled to -1°C and kept constant.	Continuous	Temperature in waterbath changed to produce different temperature gradients.
Parker (1987); Pickering (1988); Polkinghorne (1988)	Undisturbed soil blocks	Automatically controlled by microcomputer	Continuous	Investigation into influence of soil-moisture content on needle-ice growth

N.S. : not stated
N.A. : not applicable

Table 4.1 (cont.)

4.3.1 Soons and Greenland (1970)

Soons and Greenland attempted to determine the influence of repeated freeze-thaw cycles on needle-ice growth and soil-surface characteristics. Thermistors were embedded at different depths in the soil to enable vertical temperature gradients to be monitored continuously. Higashi and Corte (1971) also used this method and were able to estimate the depth of the freezing interface in the soil at any one time using the temperature data. Gypsum blocks were used to measure the moisture content within the soil sample, although with limited success.

Soil moisture was provided by thoroughly wetting the soil surface at the beginning of the first freeze-thaw cycle. Following this no further water was added. However, needle-ice growth and evaporation depleted the moisture supply and needle ice could only be grown on four successive freezing cycles.

In the first of these cycles, the growth rates of the ice crystals were between 8 mm h^{-1} in the early hours of the cycle and 1 mm h^{-1} in later stages. There was a semilogarithmic relationship between the duration of growth and the length of the ice crystals. During the first cycle two layers of ice crystals were produced, separated by a soil layer. This showed that more than one layer of crystals could be produced in one freezing cycle (Sections 3.2.1 and 3.2.3). In the remaining cycles the moisture content of the soil decreased as did the height of the ice crystals, indicating the importance of soil moisture to needle-ice growth.

Over the course of the four cycles the characteristics of the soil were observed to change. Following the first cycle the surface was covered with 'small, loose soil pellets' (p.587). Later cycles produced a puffy, friable soil surface.

Two effects of repetitive freeze-thaw cycles were recognised from the simulations. First, ice crystals became less dense in each cycle; only five or six needles were produced during the fourth cycle. Secondly, in the last three cycles the frozen soil layer at the base of the ice crystals became markedly thicker.

4.3.2 Meentemeyer and Zippin (1981)

Five different soils were examined in a series of experiments, over a range of soil-moisture contents, which were designed to determine threshold limits for the variables that control needle-ice growth. The general conclusion was that the moisture content required to produce needle ice increases as the percentage of fines in the soil decreases.

Experiments showed that ice weight increased with increased soil-moisture content. It was also suggested (from scrutiny of the relevant regression intercept) that for each soil there is a critical moisture level that must be exceeded for needle ice to grow at all. The slopes of these regression relationships could be taken to represent the rate at which water converts to ice, or as a measure of the efficiency of the soil in converting its moisture to needle ice. High clay contents, for example, will inhibit moisture migration, and reduce the efficiency of needle-ice growth.

Meentemeyer and Zippin also attempted to determine how surface texture influences the amount of soil lifted by ice. Half of the soil in the box was smoothed and the other half made rough. After freezing the needle-ice crystals and the sediment which they lifted was sampled. They found that there was no difference between the quantities of soil lifted in the two areas. This conclusion agrees with the experiments of Soons and Greenland (1970) who determined that the roughness of the soil surface had little effect on the amount of soil lifted by needle ice. A hypothesis was formulated based on field evidence that the soil must be desiccated if it is to be associated with more lift. It was expected that the amount of soil lifted would be related to the soil-moisture content. However, regression analysis showed that the relationship between soil lift and moisture content was not significant. Only one soil sample showed a negative correlation between soil weight and soil-moisture content.

It was suggested that these inconclusive results may be due to the nature of the laboratory techniques. The needle ice was allowed to melt back into the soil, thus re-wetting surface layers. Hence, although the soil surface was desiccated by evaporation in the laboratory, no dry surface crust was formed as would be expected under natural conditions.

Finally, the authors questioned whether needle ice selectively lifts particles of certain sizes. The results showed that the particle-size distribution of the lifted soil was insignificantly different from the host medium.

4.3.3 Parker (1987); Pickering (1988) and Polkinghorne (1988)

Two short-term experiments carried out in the Birmingham University Ice Laboratory represented what is thought to be the first British attempt to replicate needle-ice growth in a laboratory. These projects acted as feasibility studies for the present series of experiments (Chapter 5).

The experiments differed from previous work in that they used undisturbed soil samples (an undisturbed block of soil was cut from a river bank). Also, unlike other studies, where surface cooling was initiated by the manual operation of a thermostat, cooling of the sample was automatically controlled by a BBC micro-computer programmed with an appropriate cooling curve.

Satisfactory needle-ice crystals were produced, and in the 1988 experiments preliminary investigations were made into the influence of soil moisture on needle-ice growth. It was concluded (albeit from only five experiments) that maximum growth is achieved with a soil-moisture content of 55-60%. Further, it was suggested that critical moisture values will depend on soil composition. The rates of growth of the ice crystals were calculated to be 0.3 to 1.3 mm h^{-1}. These were average figures, calculated from information of the duration of temperature below 0°C and the final length of the crystals.

4.4 CASE STUDIES OF EXPERIMENTS ON SEDIMENT TRANSPORT BY NEEDLE ICE

As there appear to have been only two studies which have investigated the transport of sediment by needle ice under laboratory conditions the methods used in both laboratory and field investigations of transport are described here.

4.4.1 Higashi and Corte (1971)

Higashi and Corte are the only authors to publish rates of sediment transport by needle ice under laboratory conditions. Their series of experiments aimed to develop methods to measure the movement of soil particles, at the surface and at depth, and to obtain quantitative results for the processes which cause the downslope movement of particles.

Three types of marker particles were used: glass marbles (15 mm diameter), rectangular glass plates (20 x 10 x 1 mm) and pumice stones (c.10 x 10 x 10 mm). The particles were placed on the slope in lines, with 5 cm between each particle and at 2 cm depth intervals in the soil profile. The lines were 13.5 cm apart. Experiments were conducted on slopes of 3°, 7.5° and 15°.

The positions of the soil-surface particles were measured after each freeze-thaw cycle with reference to a grid on the side of the sample box. The location of the particles at depth was measured every two to three cycles. The final results were presented as average movement of the particles on each line. Higashi and Corte concluded that movement of particles by frost creep is influenced primarily by the angle of slope rather than the amount of heave.

4.4.2 Van Steijn (1977)

A series of laboratory experiments by Van Steijn attempted to measure seasonal creep by freeze-thaw action. Creep measurements were made with plastic needles 15 cm and 25 cm long, 3 mm diameter, which were inserted horizontally into the loess. The position of the needles was determined with reference to a grid on the side of the box. Two cycles of freeze-thaw were conducted, lasting 24 days and 16 days, with approximately equal freezing and thawing cycles. Due to problems with the apparatus, however, no transport data were presented.

4.4.3 Brockie (1968)

In a field study in East Otago, New Zealand, needle-ice growth was monitored with a motometer (Section 5.2.5). The data were fragmentary but indicated that factors other than soil and air temperature influenced the growth of needle ice.

White stones were randomly scattered on the surface of a disturbed plot of soil. Time-lapse photography was used to show the progressive movement of the stones downhill. Problems emerged, however, because the stones disintegrated as a result of frost action and only 59% of the stones survived the measurement period (18 months). Results from monitoring the particles suggested that there was no correlation between the amount of surface movement and number of frost cycles. Time-lapse photography was also used by Hayward and Barton (1969) in a study of sediment transport by needle ice.

4.4.4 Walton and Heilbronn (1983)

In a study of vertical movement of the soil profile in South Georgia strings of wooden dowels were inserted into the soil. They were excavated after one and two years to measure their displacement. The downslope movement of all but the top one or two dowels was slow and the top one or two were often lost. This was attributed to needle-ice growth and gravitational displacement after the crystals melted. There was a positive relationship between the movement of the top dowel and altitude.

In a series of sites on different slope angles photographs were regularly taken of fixed quadrats. Measurements of the downslope movement of native clasts in each of the quadrats were taken from the photographs. The movement data were regressed against clast size giving a mean movement rate per unit clast length. The results showed that annual movement decreased as clast size increased.

4.4.5 Pérez (1987a, b, c; 1988)

Pérez investigated the movement of painted stones and wooden pegs by needle ice in the Venezuelan Andes over five and a half years. The project aimed to show the spatial and temporal variation of movement and the factors that affect transport. He determined that slope angle had the most important (positive) influence on the rate of movement. The magnitude and frequency of movement varied significantly between the different soil types and transects on the slope.

4.5 CONCLUSIONS

The preceding review has outlined the main components of the laboratory and field experiments which were designed to investigate needle-ice growth and sediment transport by needle ice. This has enabled the common themes to be evaluated. The success and applicability of some approaches can be questioned given the nature of the soil samples and cooling profiles used.

Most experiments have used frost-susceptible soils as growth media (usually volcanic, loams or loess). The natural characteristics (grain-size distribution, bulk density and pore size) of the sediments were altered by crushing and sieving to remove large particles. The sediments were then distributed homogeneously in a box, and wetted to help compression (e.g. Soons and Greenland, 1970; Van Steijn, 1977), but the same extent of compression that existed in the original sample was probably not achieved by this method. Undisturbed samples were used in only two experiments (Parker, 1987; Pickering, 1988; Polkinghorne, 1988) and it is suggested that these should be used in future experiments.

The cooling profiles in almost all the studies were stepped; often the freezing lasted several days, and thus did not approximate natural cooling cycles very closely. Future studies should aim to simulate natural cooling cycles.

The need for a continuous water supply was evident from the study of Soons and Greenland (1970) who were unable to replicate more than four needle-ice events due to the lack of a water bath. The experiments of Kinbacher and Laude (1955), Corte (1967) and Higashi and Corte (1971) used a continuously available moisture supply. A water reservoir was placed beneath the soil sample. In some instances wicks were extended into the water reservoir from the soil to improve vertical water flow.

The measurement of temperature and soil moisture within the soil profile is important in studies of needle ice. The former has been successfully monitored by Higashi (1958) and Soons and Greenland (1970) and has been solved by the introduction of thermistors and data-logging in recent years. Measuring soil moisture within the soil block has been attempted in only two experiments (Soons and Greenland, 1970; Van Steijn, 1977), and then with only limited success. It is thus important that future studies should try to achieve the continuous monitoring of absolute measures of soil moisture.

The rate of needle-ice growth has been calculated from the ultimate length of the ice crystals divided by duration of sub-freezing temperatures. This assumes that growth is linear with time and does not allow for discontinuous growth. It is therefore evident that continuous recording of crystal length during growth is required, using similar techniques to those used to measure heave in other periglacial studies (see Section 5.2.5).

The present study has aimed to build on the methods used in previous needle-ice laboratory experiments and specifically incorporate more automatic monitoring of the key variables. The techniques used are described in Chapter 5.

Chapter 5

METHODS

5.1 INTRODUCTION

This chapter describes the instrumentation used in the needle-ice simulations, sensor calibrations and experimental procedures. Details of the instruments and their accuracy and resolution are presented in Appendix 2. Sections 5.2 and 5.3 describe the equipment and procedures used for the first-stage experiments which investigated needle-ice growth and sediment incorporation. Following this, the methods used to analyse resultant needle-ice and soil samples are described. The next two sections discuss the second-stage experiments which investigated the rates and processes of sediment transport.

The apparatus used for the experiments is shown in Figure 5.1, Plate 5.1 and Plate 5.2. The rationale behind the design is to allow the control of key variables that are thought to influence the process of needle-ice growth, and to assess their relative importance to the processes of soil erosion and transport. These factors include soil-surface temperature, cooling rate, soil-moisture content and slope angle.

5.2 EXPERIMENTAL DESIGN: NEEDLE-ICE GROWTH AND SEDIMENT INCORPORATION EXPERIMENTS

Two phases of experimental design are referred to in this section:

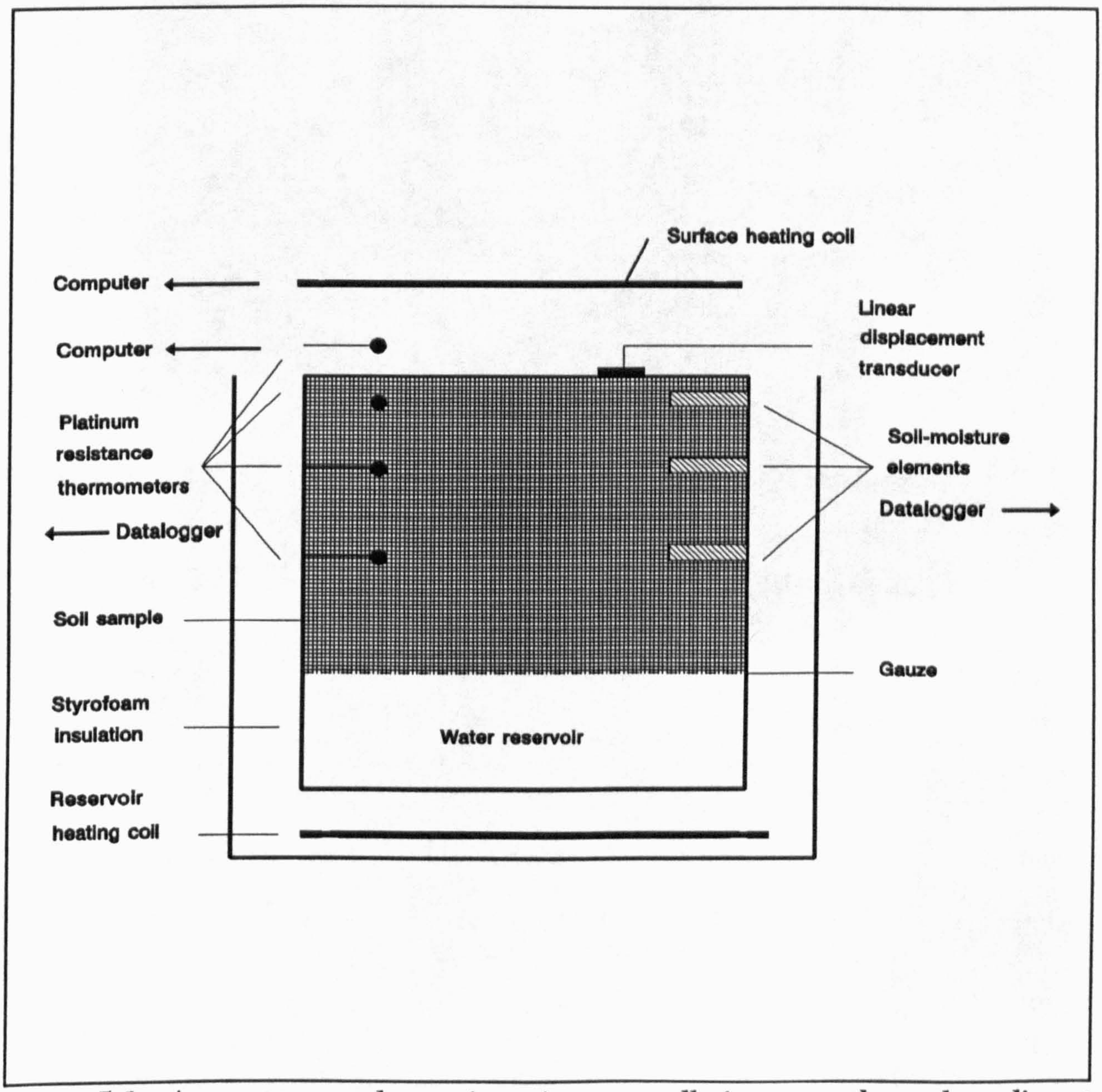

Figure 5.1 : Apparatus used to investigate needle-ice growth and sediment incorporation (not to scale)

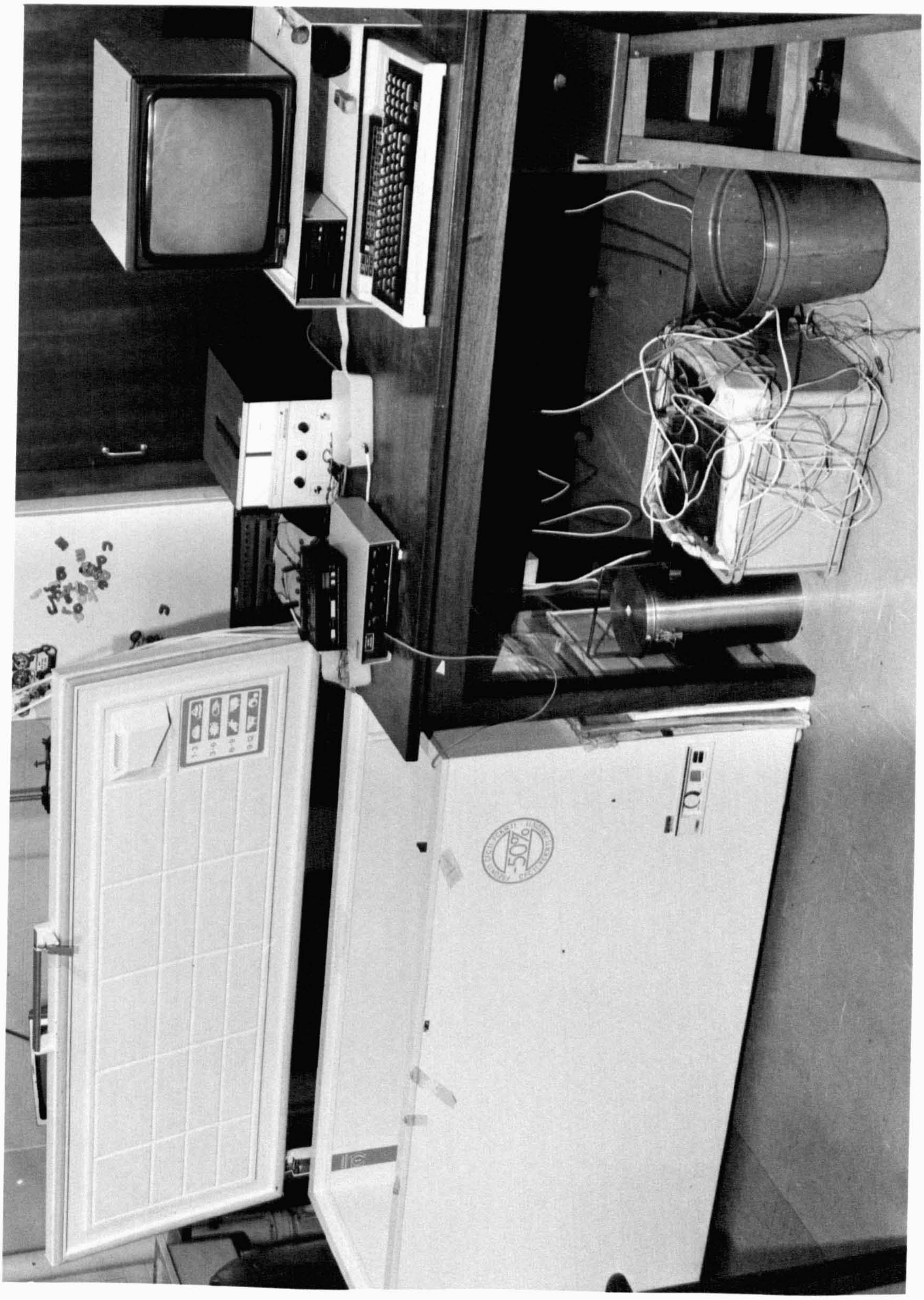

Plate 5.1 : The needle-ice experiment, showing cooling chamber, BBC microcomputer, power supplies and sample box

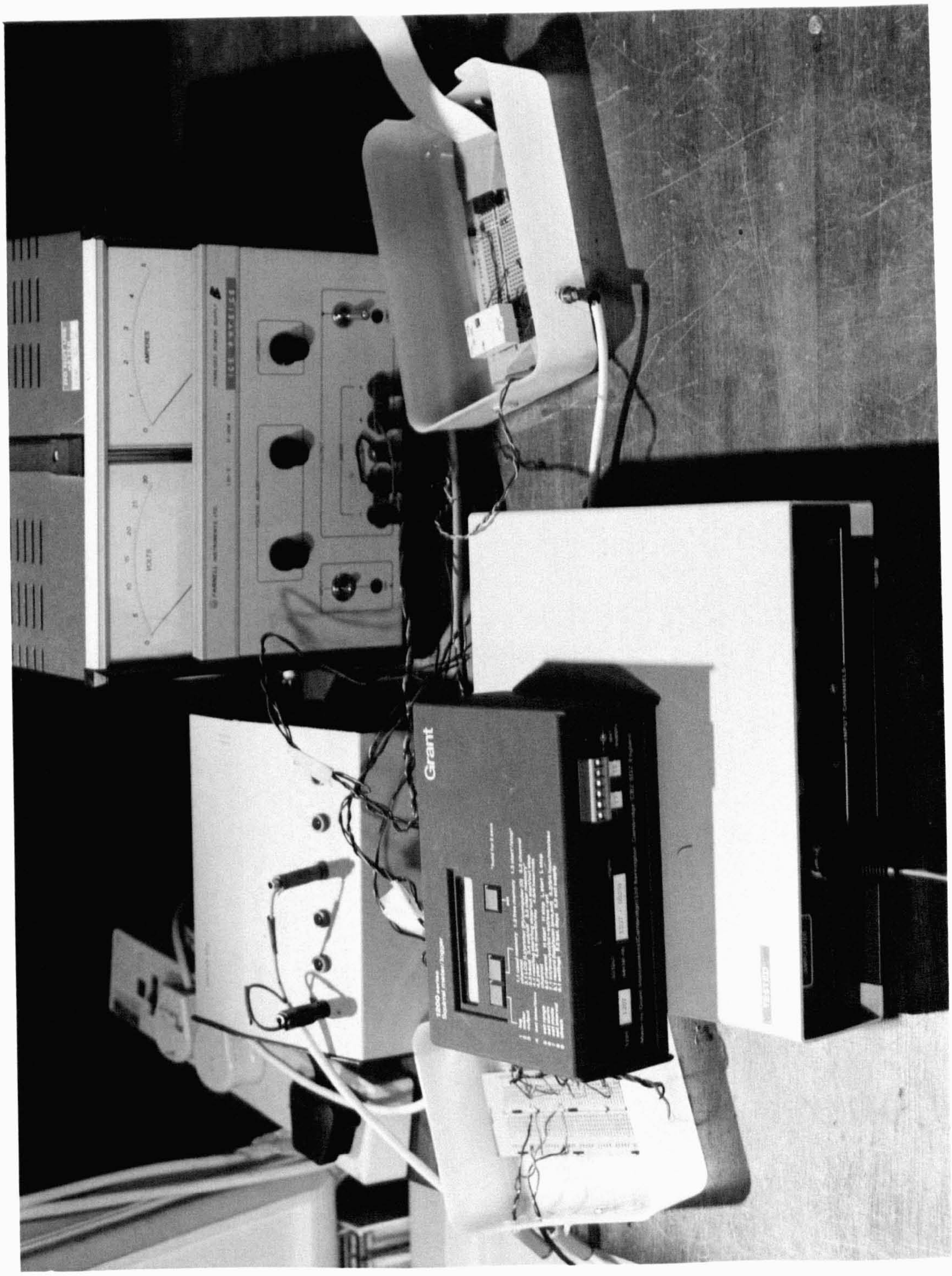

Plate 5.2 : The needle-ice experiment, showing power supplies (top), moisture element circuit (middle left), relay circuit (middle right), datalogger and temperature control unit

i) preliminary experiments, principally designed to test the apparatus;

ii) a second phase of experiments designed to investigate the influence of temperature, soil-surface cooling rates, moisture content and moisture migration on needle-ice growth and sediment incorporation.

5.2.1 Growth Medium

Both undisturbed and remoulded soil samples were used in the experiments, from two locations where needle ice has been observed to grow naturally (see below). The majority of earlier studies have used disturbed samples (Chapter 4).

Arguments both for and against soil disturbance have been presented. Corte (1967), for example, stated that, during freezing and thawing cycles, soils are subjected to changes in characteristics such as bulk density which are irreversible. Soils will thus be affected differently by each freezing and thawing cycle. The Polar Research Board (1984; p.17) stated that 'heaving always results in irreversible changes in the structure of soils ... ice segregation also causes changes in the hydraulic conductivities of soils ... the structural changes caused by the increased effective stress within the "frozen fringe" or in the unfrozen zone beneath the freezing front are known to cause large increases in the thawed hydraulic conductivities of soft clay soils, whereas the disintegration of soil aggregates that is caused by ice segregation in some silty soils result in lower hydraulic conductivities.' It may therefore be preferable to use a remoulded sample so that a 'new' soil is produced that has not been previously affected by frost action. All soil samples used for the experiments will thus start with similar characteristics.

Linell and Kaplar (1959), however, suggested that the remoulding and manipulation of fine grained soil reduces its susceptibility to frost. Similar handling of a coarse sample, however, may increase its frost susceptibility due to the degradation of particles and manufacture of additional fines.

5.2.1a Remoulded samples. Remoulded samples were taken from two locations. Samples DSE_1 and DSE_2 were taken from a garden in Edgbaston, Birmingham, where needle-ice growth was observed during winter 1990. Samples DSB_1 and DSB_2 were taken from the river bank of the Bournbrook, Selly Oak, Birmingham where prolific needle-ice growth was observed in Spring 1986 (Lawler, Pers. Comm.). The samples were dry sieved through a 4 mm sieve to remove large stones, distributed homogeneously in the sample box and then compacted by pouring water onto the surface (Soons and Greenland, 1970; Van Steijn, 1977). The grain-size distribution of these samples DSE_1 and $DSB_2$is shown in Figure 5.2.

5.2.1b Undisturbed samples. Undisturbed blocks of soil (USB_1 and USB_2) were also used. These were cut from the same location on the bank of the Bournbrook as DSB_1 and DSB_2 (see above). Each block was placed into the sample box (Figure 5.1) (which measured 30 x 30 x 20 cm) such that the stream-facing side of the sample (i.e. the part that was affected by needle-ice growth under natural conditions) was the top surface of the sample box. The grain-size distribution of these soils is shown in Figure 5.3.

5.2.2 Water supply

The bottom half of the soil sample box contained a water reservoir to provide a constant supply of water to the sample (Figure 5.1). This was topped up to the same level before each experiment (to cover the bottom 10 mm of the soil sample). Underneath the reservoir there was a piece of resistance wire, which was used as a heating coil (Figure 5.1). This coil prevented the water reservoir freezing and also provided a source of heat to the base of the soil, to simulate the ground heat flux. The temperature of the water during the experiments was 3 to 4°C.

Experiments without this source of heat failed to produce satisfactory samples of needle ice, and the soil often became frozen in-situ. This was because the rate of heat removal at the soil surface exceeded the amount of heat flow to the surface (which was negligible). Conversely, if too much

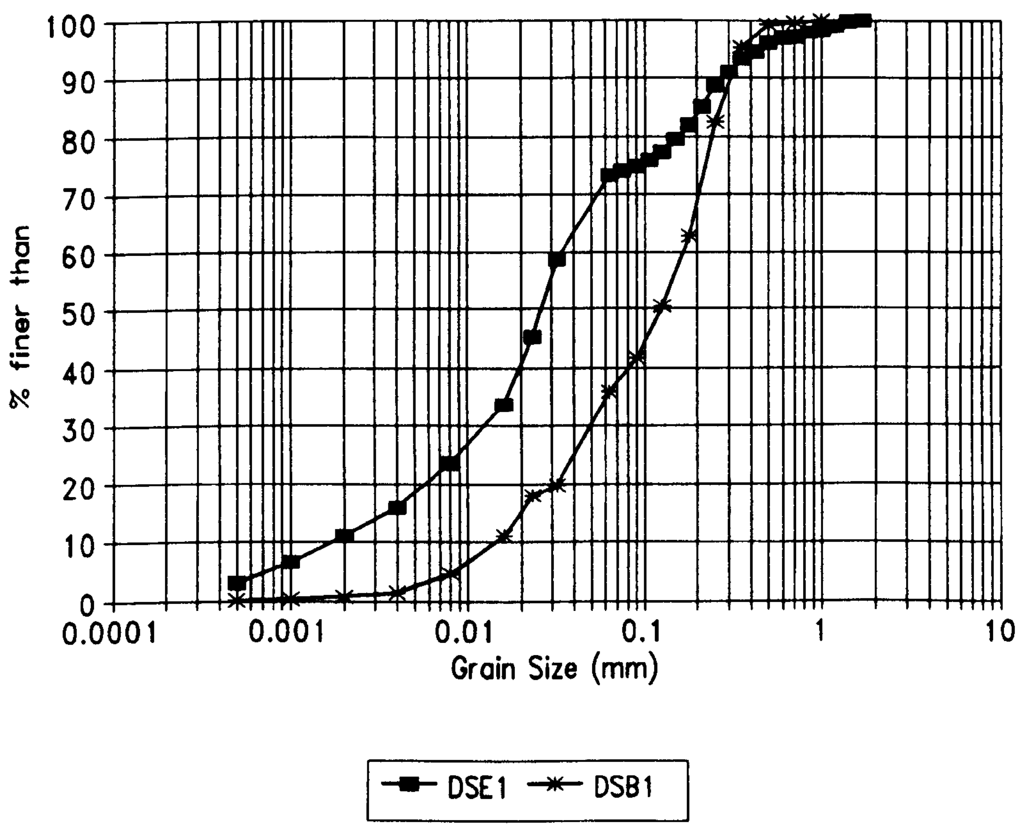

Figure 5.2 : Grain-size distribution of the disturbed soil samples

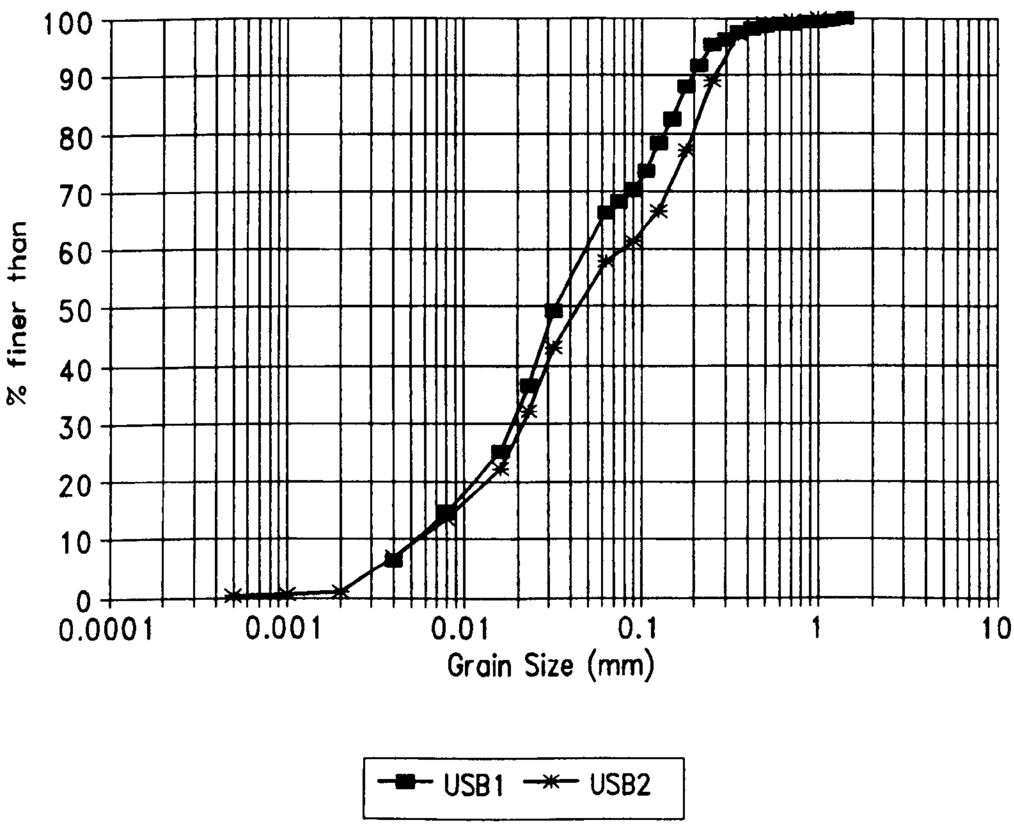

Figure 5.3 : Grain-size distribution of the undisturbed soil samples

heat was supplied to the soil surface needle-ice growth was also prevented (Section 6.2.2). The heating coil power therefore influenced the temperature profile of the soil sample and thus needle-ice growth. In these experiments it was important to keep the flow of current to the heating coil low and constant (the power of the heating coil was c.25 W).

5.2.3 Temperature measurement and control

For the preliminary experiments a small upright domestic refrigerator was used as a cold cabinet. This was modified to include perspex doors that allowed observation of the sample whilst cooling was taking place. Later experiments used a large chest freezer (fitted with a perspex top) which provided more space for the instrumentation.

Several Grant Instrument mini-thermistors (resistance thermometers) were used in the preliminary experiments to monitor temperatures. To prevent the resistance values being affected by moisture the contacts were covered with non-conductive heat shrink plastic (Van Steijn, 1977).

The resistance of the thermistors was measured using a Wheatstone bridge circuit (Horowitz and Hill, 1988). The output from this was sent to the analogue-to-digital converter (ADVAL) socket of a BBC microcomputer. This signal was converted into a temperature value using a pre-programmed calibration curve (Section 5.3.1).

The thermistors were calibrated before each experiment through a cooling cycle. The thermistors and a platinum resistance thermometer (with which to determine temperature) were put into the cooling cabinet which was allowed to cool. The output of the thermistors indicated as an ADVAL value by the computer and the temperature were recorded every two minutes. An equation by which the temperature (dependent variable) could be determined from the ADVAL value (independent variable) was produced by regression analysis (e.g. Figure 5.4). (There was a separate equation for each thermistor.) The results of the calibrations were very good, and the standard errors of the temperature estimates were low (e.g. Figure 5.4). The ADVAL values were subsequently converted into temperatures within the control programme (e.g. Appendix 3).

The second phase of experiments (which investigated needle-ice growth and the erosion and transport of sediment by needle ice) used platinum resistance thermometers to give greater accuracy in temperature measurement (Plate 5.3). The output from the platinum resistance thermometers was read by a four channel thermocouple amplifier, designed to monitor temperatures between -15 and +15°C. The output from the amplifier was recorded by a datalogger (Section 5.2.6). 1°C was represented by 12.903 mV. The thermometers were calibrated by placing them in a water and ice bath that was continuously stirred and the mV output of each thermometer at 0°C was measured. This was to determine the difference between the actual output at 0°C and the design output which was 0 mV. The temperatures were determined when information from a datalogger was downloaded into a personal computer by

$$T=\frac{(P-P_0)}{12.903} \tag{5.1}$$

Where T is temperature (°C), P the output of the platinum resistance thermometer (mV) and P_0 the output of the platinum resistance thermometer at 0°C (mV). There was a separate value of P_0 for each thermometer.

The cooling sequences used in the experiments were initiated using an ordinary domestic refrigerator and microcomputer. One of the thermistors/platinum resistance thermometers was used with a BBC microcomputer to control the soil-surface temperature through a simple feedback system (see below). In this respect the study varied from most other laboratory experiments of needle-ice where temperature changes within the cold cabinet were controlled manually (Chapter 4).

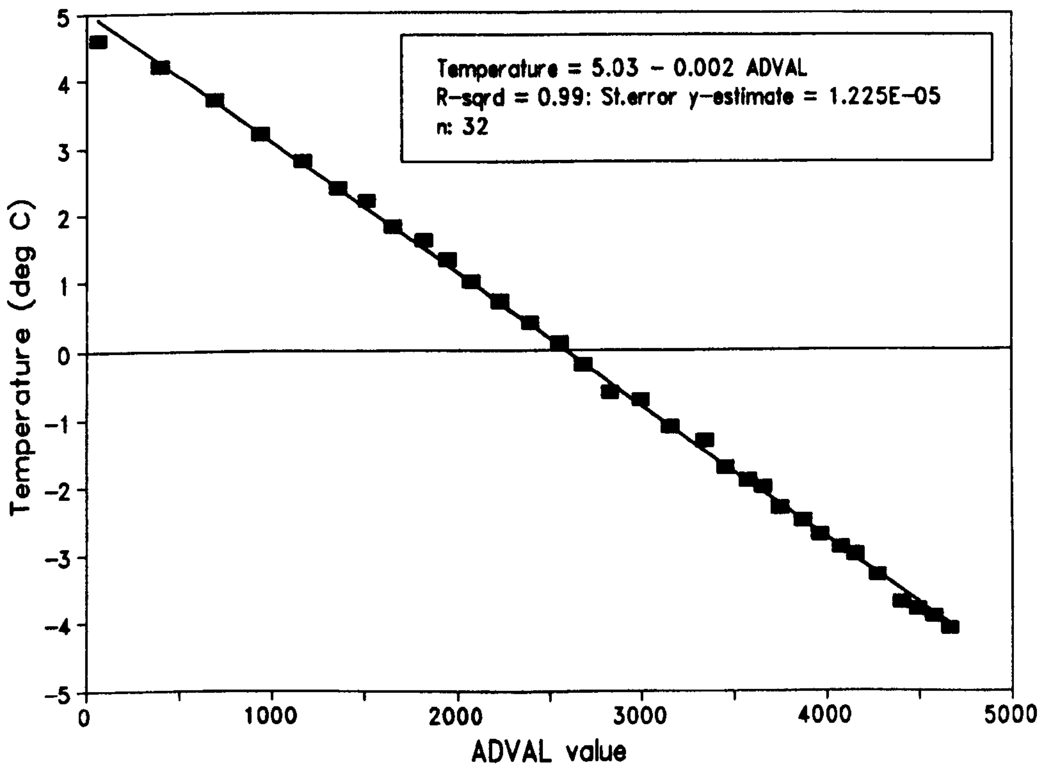

Figure 5.4 : Typical calibration plot for a thermistor

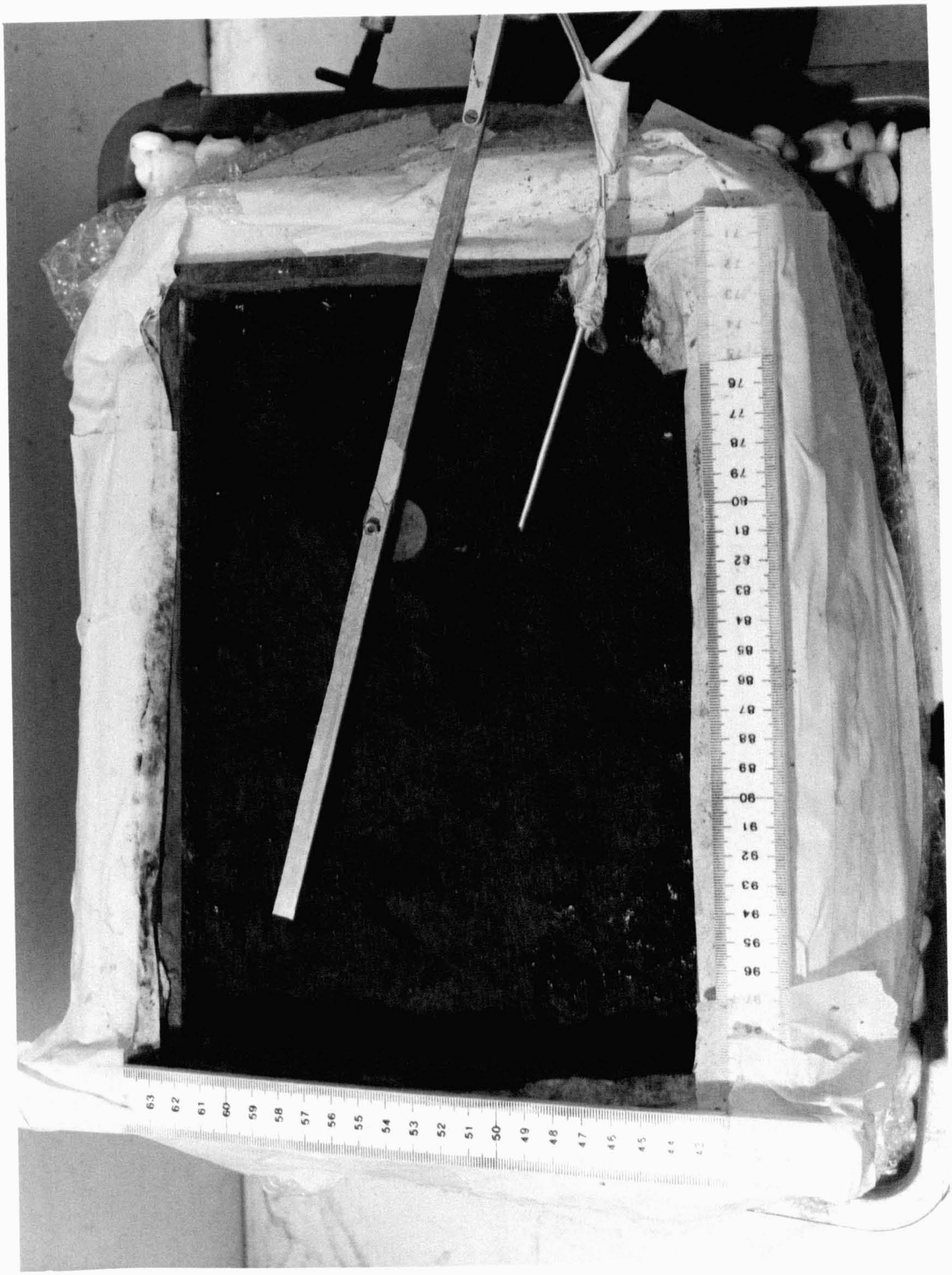

Plate 5.3 : Platinum resistance thermometer (bottom) and soil heave plate (top) on the soil surface

Several data-arrays were established in the computer memory which contained time-temperature values for the cooling profiles required. These arrays contained between 80 and 360 temperature values, and the cooling profiles lasted between ten and 36 hours. (An example of the control programme is given in Appendix 3.) The temperature values in the array were known as the 'required temperature' (T_r). The aim was that the temperature at the soil surface should follow that stipulated in the array. The actual temperature at the soil surface (T_a), as indicated by the thermistor, was compared to the required temperature every 10 s. If $T_a < T_r$ then a relay circuit connected to the 'user port' of the BBC computer automatically switched on a heating coil just above the soil surface (Figure 5.1). When $T_a = T_r$ the relay switched off the heating coil. The value of T_a was monitored, and any necessary heating delivered, every ten seconds. Figure 5.5 shows a typical correspondence between T_a and T_r during two experimental runs. Replication was always to within ± 0.2°C. The refrigerator was such that the actual temperature exceeded the required temperature on only several occasions during the series of 170 experiments. It was not possible to compensate for this with the apparatus, however.

The cooling rate of the soil sample is thought to be a critical factor for the laboratory simulation of needle ice, in that it should be slow enough to simulate natural cooling, which is usually a result of radiative heat loss (Higashi and Corte, 1971). Outcalt (1970b), after observing the role of radiation and shielding in enhancing or restricting needle-ice growth, suggested that it is important to replicate radiative cooling in the laboratory, . The fact that many experiments (including the present study) without such a cooling mechanism have successfully reproduced needle ice shows that radiative cooling itself is not essential. J.M. Sayward (Pers. Comm. to D.M. Lawler) stated that given the appropriate temperatures in the immediate surroundings, then sky radiation is not a necessity.

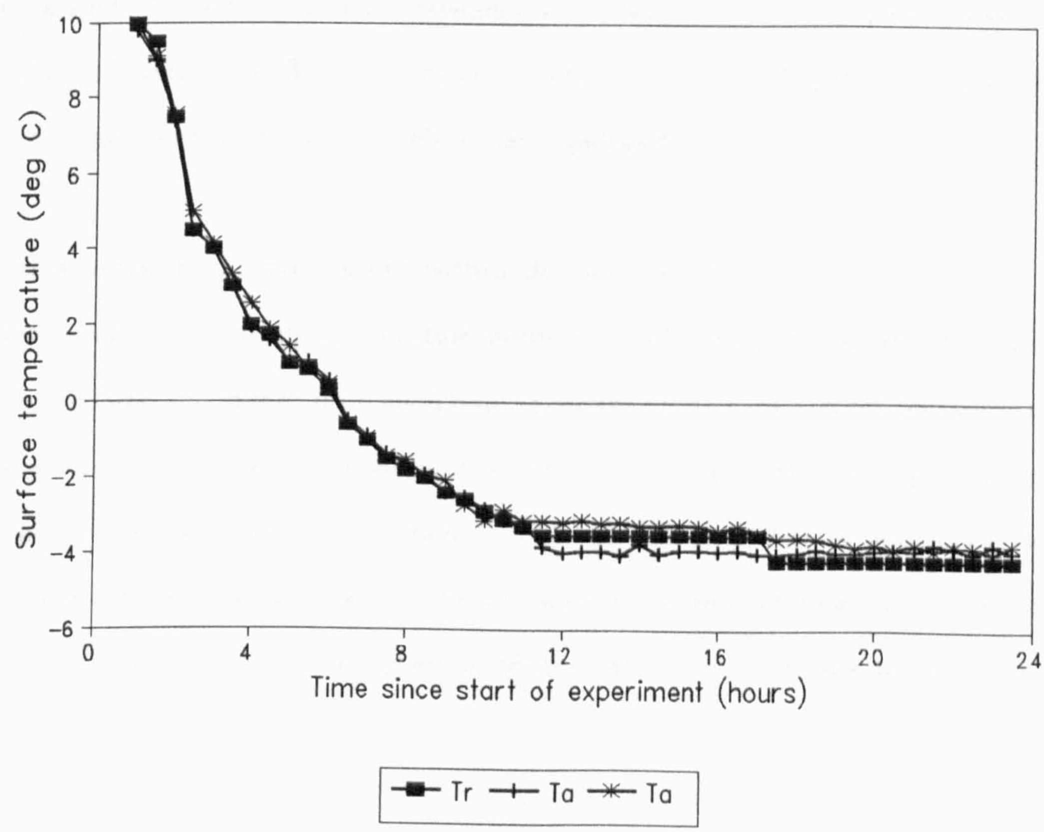

Figure 5.5 : Typical correspondence between T_r and T_a for two experimental runs

Another concern was that the rate of cooling is, to a certain extent, controlled by inputting heat at the soil surface. Despite these problems, however, satisfactory samples of needle ice which were similar to samples found in the field were produced by Parker (1987), Pickering (1988) and Polkinghorne (1988) using this procedure. This suggests that, for the purpose of the present study, which is mainly concerned with sediment incorporation and transport at the soil surface the mechanism of cooling is not crucial.

Two thermistors (or three platinum resistance thermometers in later experiments) were placed within the soil sample, 1, 3 and 5 cm below the soil surface (Figure 5.1). This allowed the temperature gradient in the soil sample to be monitored.

5.2.4 Soil-moisture measurement within the soil sample

The importance of measuring soil moisture in the study of needle ice was recognised by Brockie (1968; p.193) who stated that 'until such time as improved instrumentation, including continuous recordings of soil moisture, is available, it seems unlikely that ... the predisposing condition for its [needle-ice] growth can be determined'. The only other studies of needle ice which have directly monitored soil moisture within the soil sample are those of Soons and Greenland (1970) and Van Steijn (1977), who used gypsum blocks and nylon elements respectively, but with limited success.

Soil-moisture movement during the freezing cycles was monitored continuously using Eijkelkamp nylon moisture elements placed at the same depths as the thermometers, but on the opposite side of the block (Figure 5.1 and Plate 5.4). Nylon elements were used in preference to gypsum blocks because they are more resistant to sub-zero temperatures, and they are more sensitive at the 'wet' end of the soil moisture range.

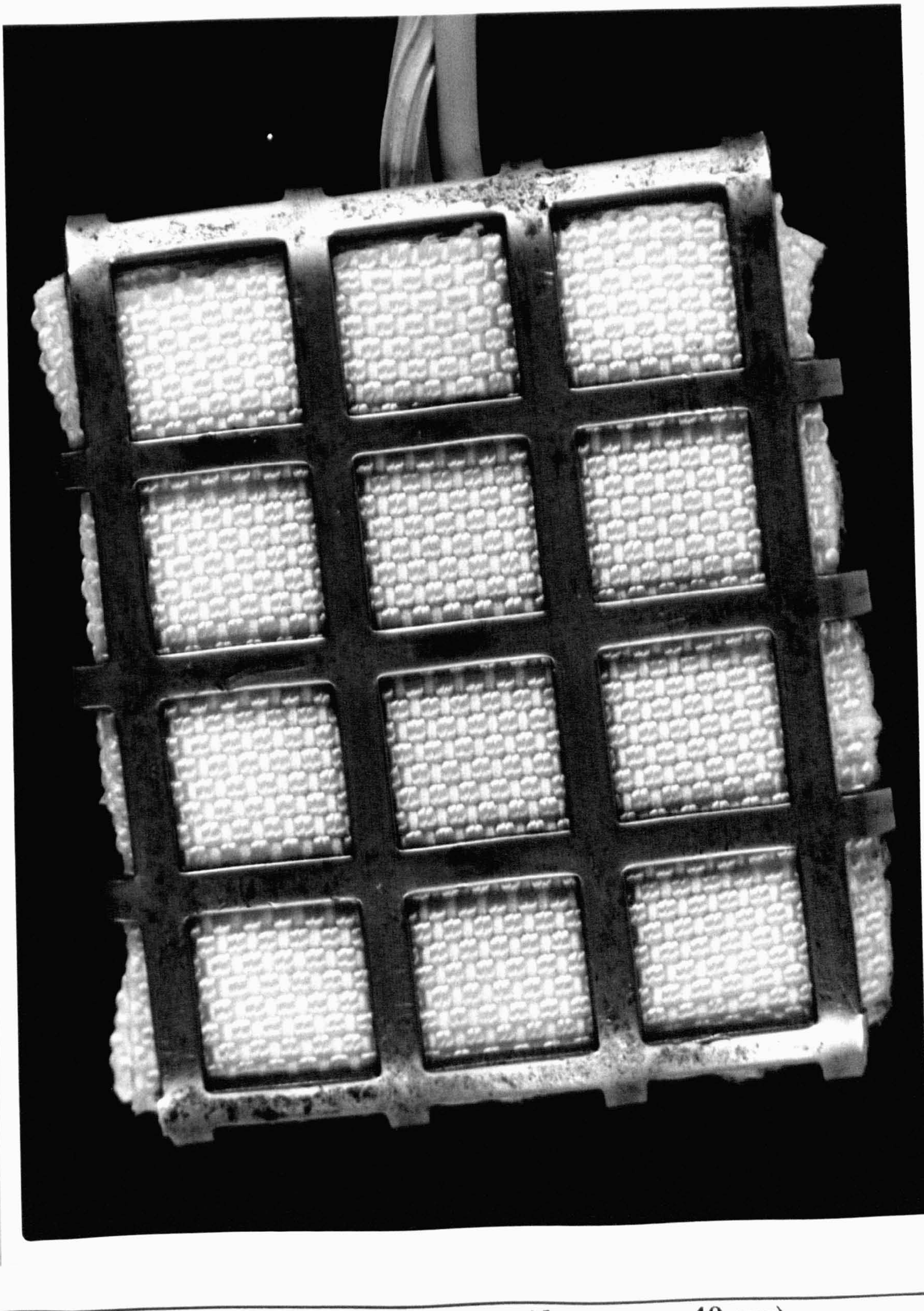

Plate 5.4 : A soil-moisture element (longest side measures 40 mm)

The elements consist of two electrodes kept at a constant distance apart by nylon cloth and protected by a metal grid (the whole element measures 40 x 40 x 5 mm). Once the element is placed in the soil, water enters the porous block until it comes into equilibrium with the matric (or capillary) potential of the soil. The electrical potential difference between the two electrodes is inversely proportional to the moisture content of the porous block, which should change as soil moisture changes during a freezing cycle. Response times and time lags were not determined but are thought to be small.

Essery *et al.* (1987; p.286) stated that 'soil moisture probes are not the most accurate method of measuring absolute soil moisture levels and any attempt to produce absolute measurements is fraught with experimental problems'. In their study they were only interested in the movement of the wetting front in the soil (i.e. relative moisture content), and thus they only calibrated one specific probe and used the calibration curve for the other probes. They stress, however, that if absolute measurement of moisture content is required then each probe should be calibrated individually. In this study, therefore, the blocks were calibrated separately using the method outlined below.

1) Before the elements were calibrated they were passed through several wetting and drying cycles to stabilise them (Essery *et al.*, 1987).
2) A sample of oven-dried soil of a known weight from the same location as the soil block was put into a container lined with a nylon bag and the element placed in the middle of the soil. The soil was compacted to ensure a good contact between the block and the soil.
3) 5 ml of water was poured onto the sample, which was then covered to prevent evaporation and left to equilibrate for four hours.

4) The voltage between the two electrodes of the element was then measured using a datalogger, and the sample container and contents weighed. The moisture content of the sample was determined by the following

$$M = 100\left(\frac{W_w - W_d}{W_d - C}\right) \tag{5.2}$$

Where M is the soil-moisture content (% dry weight), W_w and W_d the weight of the wet and dry soil respectively and C the weight of the container, nylon bag and element (after Curtis and Trudgill, 1974).

5) Steps (3) and (4) were repeated until the soil was saturated.

6) The nylon bag which contained the soil and element was then removed from the container and the sample left to air dry in the laboratory (at a temperature of c.18°C). The weight of the sample and voltage output was determined every four hours until no further change in voltage was detected.

7) Steps (2) to (5) were repeated three times for each element and calibration curves drawn (e.g. Figure 5.6). Good results were obtained from the calibrations and the standard errors were 1.5 to 3% soil-moisture content (e.g. Figure 5.6).

In addition to measurement with the moisture elements the soil-moisture content at the soil surface was determined by the standard gravimetric method (Whalley, 1990). Samples were taken from the soil surface prior to each run, immediately following freezing (soil beneath the crystals) and then after needle-ice melt.

5.2.5 Soil heave

No previous laboratory studies of needle ice have monitored the growth rate of needle ice automatically and continuously whilst the crystals are growing, but have instead inferred the rate using information about the final length of the crystals and the time period of freezing conditions.

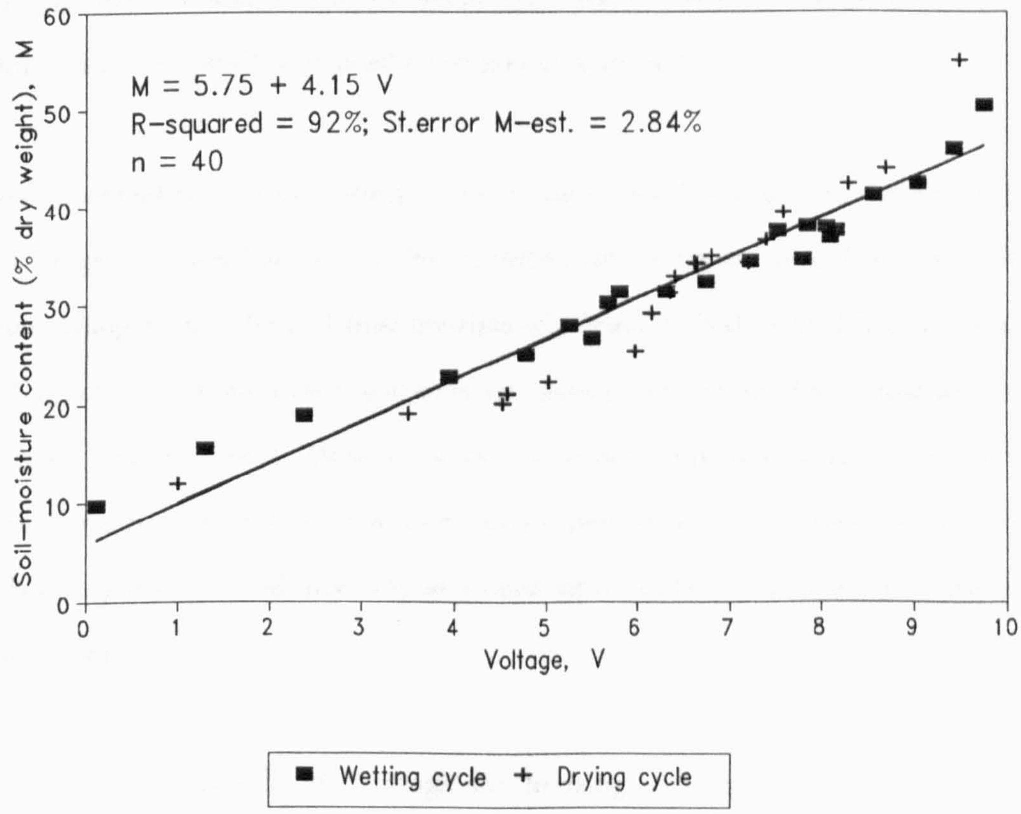

Figure 5.6 : Soil-moisture content and voltage (from the moisture element)

This method is less than totally satisfactory, however, because the rate of needle-ice growth varies during a freezing cycle (e.g. Section 6.1 and 6.3). Thus, the data can only be used to infer the average growth rate through the freezing cycle.

Some field studies of needle ice in the field (e.g. Brockie, 1968; Harris, 1973, Jahn, 1985) used a motometer (an inverted metal mushroom (Brockie, 1968)) that rested on the soil surface. Needle-ice growth is transmitted mechanically to a rotating drum. Another field study (Konkô *et al.*, 1957) used a simple displacement transducer connected to a chart recorder and successfully obtained profiles of needle-ice growth and melt.

In studies of permafrost a wide variety of techniques have been used to monitor surface heave produced by growing ice lenses etc. The Schefferville 'bedstead' (e.g. Matthews, 1962) is the most usual arrangement. The bedstead consists of a frame bolted to steel legs and rooted in the ground. A number of aluminium heave rods are passed through the frame that are free to move up and down (Smith, 1987). Measurements are usually taken manually once a week, with perhaps one arm recording daily movement with a pen trace. This method is unsuitable for use in the laboratory due to its ability only to record movements in the order of centimetres rather than in millimetres.

The rate of growth of needle ice through the freezing and thawing cycles in this study was measured using two Sangamo Western Controls Ltd linear variable displacement transducers (LVDT) attached to an armature/push rod assembly (Plate 5.3). When the transducer was attached to a 10 V dc power supply the voltage output is proportional to the displacement of the armature. The LVDT was calibrated by measuring voltage output at different known displacements of the armature (e.g. Figure 5.7). The calibration results were very good, with a 95% confidence that measurements are accurate to ±0.4 mm.

During experiments a perspex disc of 15 mm diameter (clear, to allow observation of the area being monitored) was attached to the armature and placed on the soil surface (Figure 5.1 and Plate 5.3). The disc moved up and down as the needle ice grew and melted, and did not appear to affect needle-ice growth. The discs were placed on the same point on the soil surface for each experiment.

Several of the profiles of needle-ice growth showed an irregular pattern, whereby periods of slow or no growth were followed by a sharp increase in the length of the needle ice (Chapter 6). To test whether this was caused by inertial effects in the displacement transducer as it was pushed up by the ice crystals a further calibration was carried out. The transducers were tested using an Instron Table Model Tensile Testing Machine. The 'heave discs' were placed onto a plate that executed two cycles of up and down movement. This was designed to simulate needle-ice growth and melt at approximately the same rates as in the experiments. The results illustrate that the transducers move up and down smoothly without sudden jumps (Figure 5.8).

5.2.6 Data acquisition

Two types of data-acquisition system were used in the experiments; a BBC microcomputer (which was also used to control the soil-surface temperature) and a Grant Instruments 1207 datalogger. Measurements were taken automatically at a required interval, which in the preliminary experiments was every 10 minutes and in the remainder of experiments every 2 minutes.

In the preliminary experiments the computer was used to record both soil-surface temperature and temperatures within the soil profile. In later experiments the computer was used only to record soil-surface temperature, the datalogger being used for all other measurements.

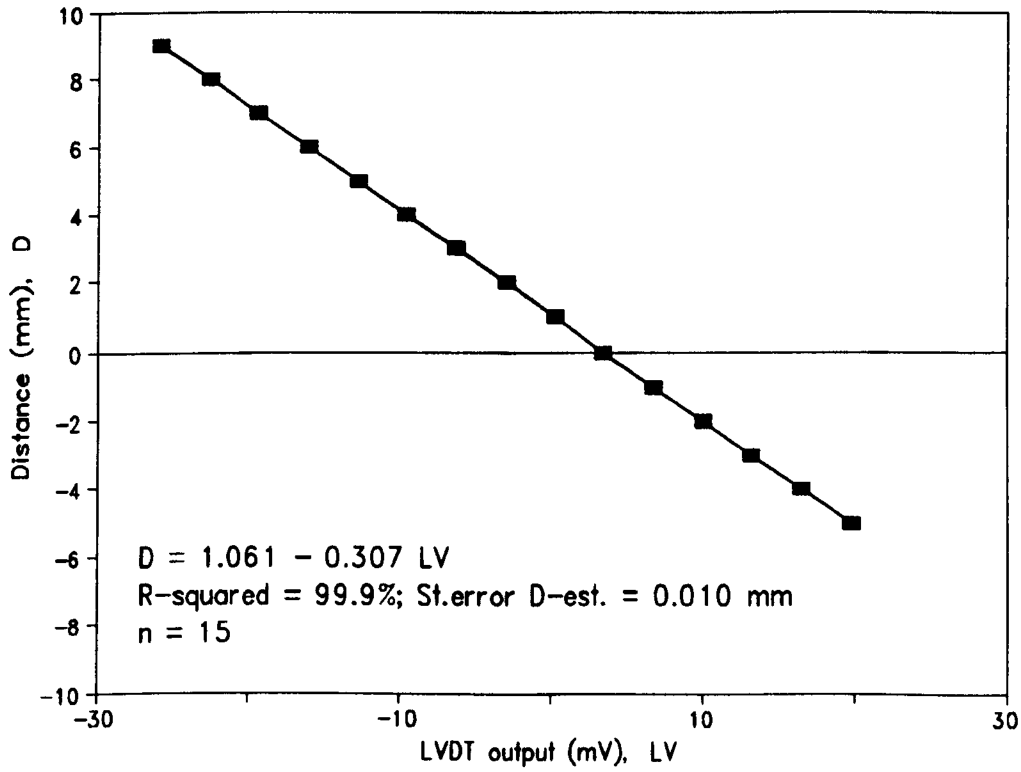

Figure 5.7 : Calibration for LVDT(1)

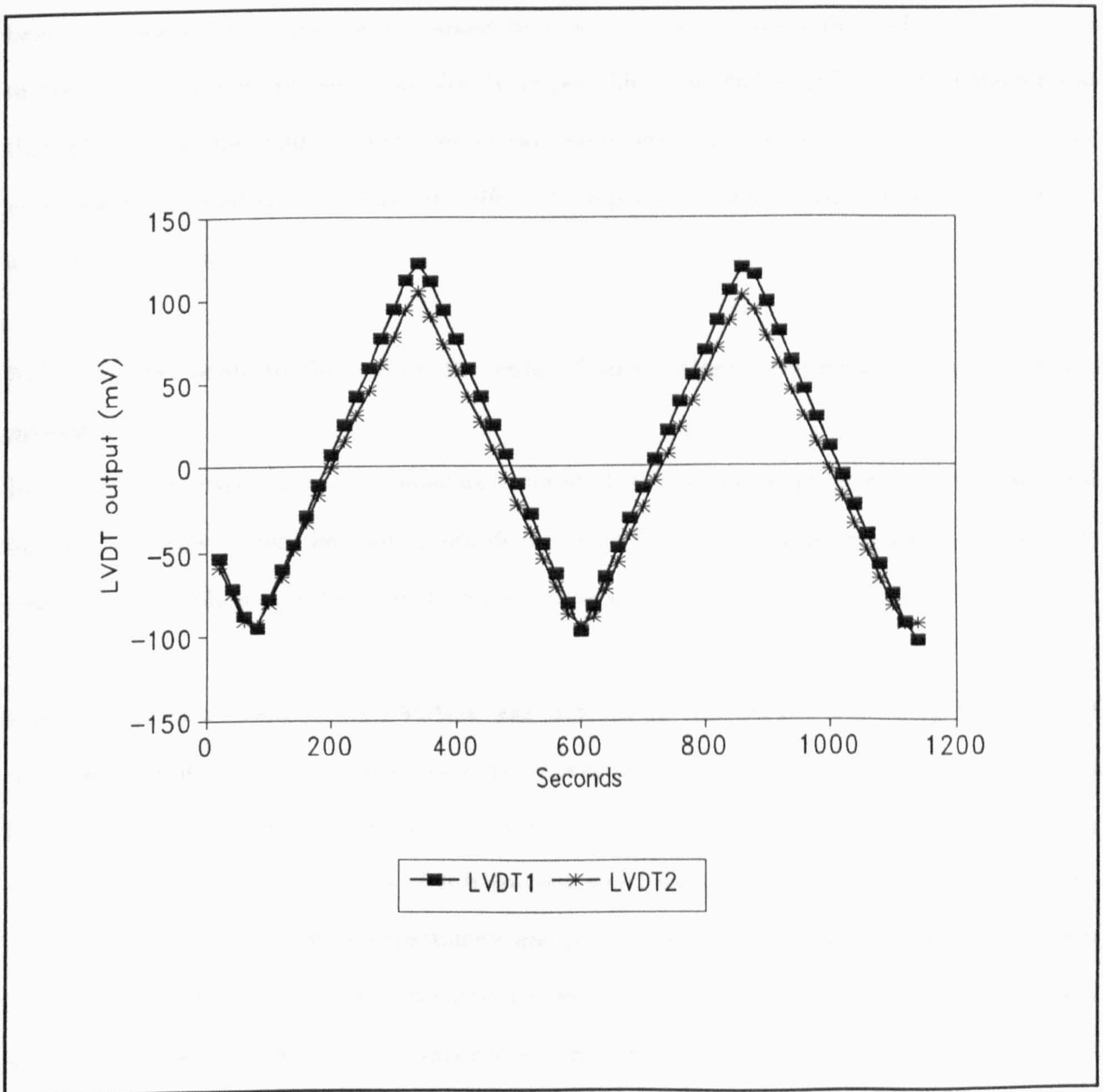

Figure 5.8 : Testing the LVDTs through 'heave' and 'melt' cycles

5.3 EXPERIMENTAL PROCEDURE: NEEDLE-ICE GROWTH AND SEDIMENT INCORPORATION EXPERIMENTS

The soil sample box was put into a larger plastic container. This container was insulated on the base and four sides so that cooling would be unidirectional (towards the surface, designed to mimic natural cooling processes as closely as possible (Van Steijn, 1977). The container was then placed into the cold cabinet. One of two main procedures were carried out prior to the experiments, depending on whether the effect of temperature, or moisture, on needle-ice growth was being examined.

5.3.1 Experiments to determine the role of soil-surface temperature on needle-ice growth

In this series of experiments the moisture content of the soil was kept approximately the same for each experiment and the cooling profile was varied. These experiments were performed to determine the influence of the rate of cooling on needle-ice growth and sediment incorporation.

Prior to each experiment the soil surface was dried using an infra-red heat lamp. Two litres of water were poured onto the soil surface. (To ensure that the soil surface was wetted evenly a frame with a closely spaced regular grid of holes was placed on top of the sample and water poured onto it. The effectiveness of this method was tested by placing the frame over a box divided into watertight 1 cm^3 compartments and pouring water into the frame. The level of water in each of the compartments was measured and was found to be equal.) The sample was covered with plastic sheeting (to prevent evaporation) and left to equilibrate for at least four hours. Meentemeyer and Zippin (1981) found that equilibrium wetness was attained three to four hours after adding the water. The length of the equilibration period required will depend to a certain extent on the texture of the soil. Fine soils will take longer to equilibrate because of their low hydraulic conductivity.

Following equilibration the sample was put into the cold chamber and cooled. Several different cooling profiles were used to allow the effect of varying rates of heat removal on needle-ice growth and associated processes to be determined. The profiles used are shown in Figure 5.9 and Figure 5.10.

Profiles A and B (Figure 5.9) represent 1°C h^{-1} and 2°C h^{-1} cooling rates, whilst profile C simulates a constant rate of heat extraction from the soil surface. These profiles, however, whilst providing a closely controlled environment, do not replicate natural conditions. Therefore, other profiles were used (Figure 5.10) which are closer to the cooling regimes experienced in nature which are often characterised by rapid early heat loss and then slower rates of cooling. Profile E, for example, includes two sudden decreases in soil-surface temperature, perhaps caused by an increase in wind velocity or by the sky clearing on a cloudy night.

5.3.2 Experiments to determine the role of soil-moisture content on needle-ice growth

In this series of experiments an attempt was made to keep the rate of cooling of the sample similar for each run whilst the soil-moisture content was varied. Two different methods of moisture control were used. The first method was designed to investigate the influence of different moisture contents on needle-ice growth, whilst the second aimed to determine the effect of moisture migration on the initiation of ice segregation.

For the first method the soil was dried with a heat lamp prior to each experiment until the soil surface was dry. Then varying amounts of water from 0.2 litres to 2 litres in 0.2 litre increments was poured onto the surface of the soil sample and left to equilibrate as described above. All samples were subjected to cooling profile D (Figure 5.10). The experiments were repeated three to four times for each moisture content.

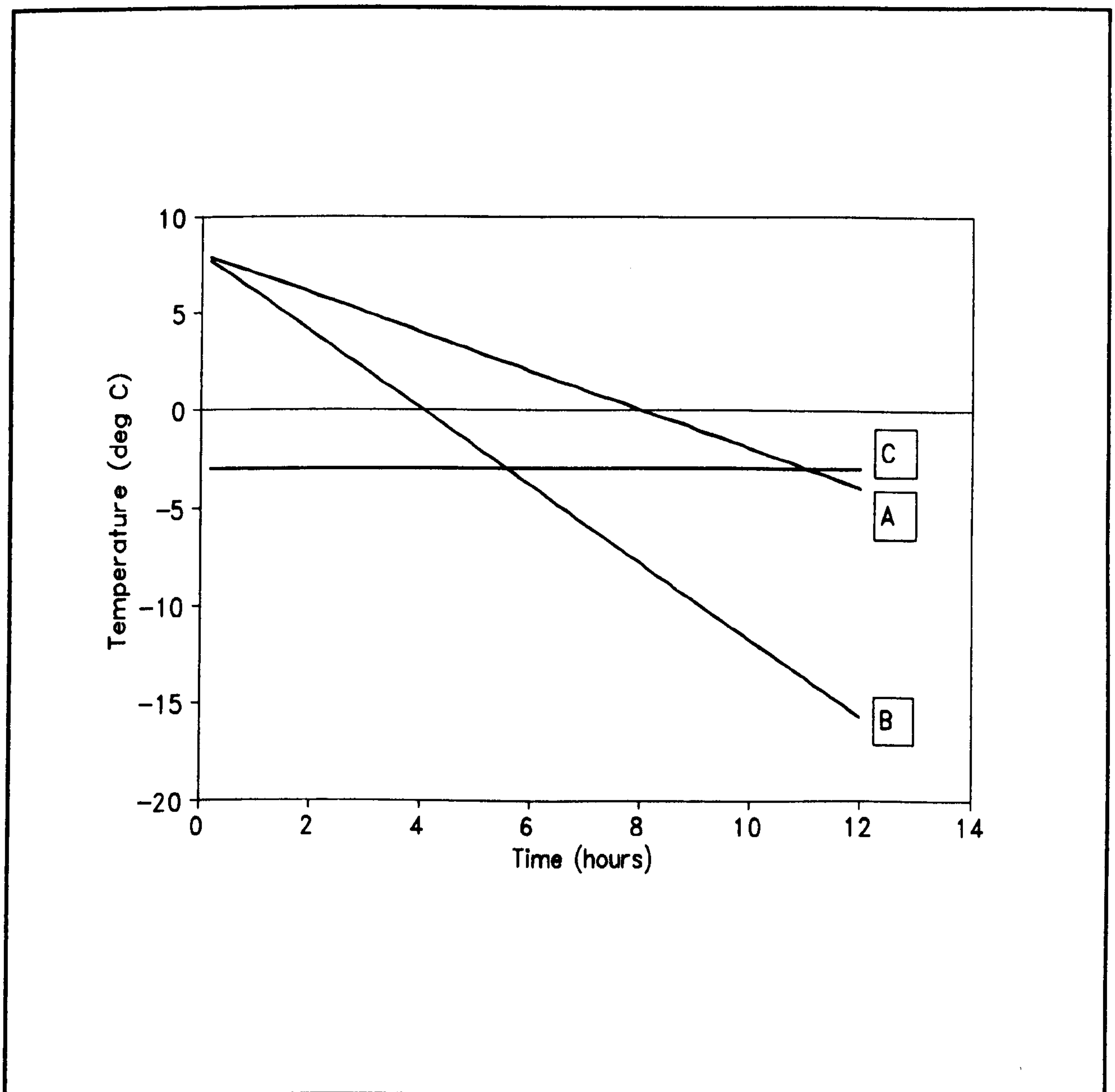

Figure 5.9 : Cooling profiles A, B and C

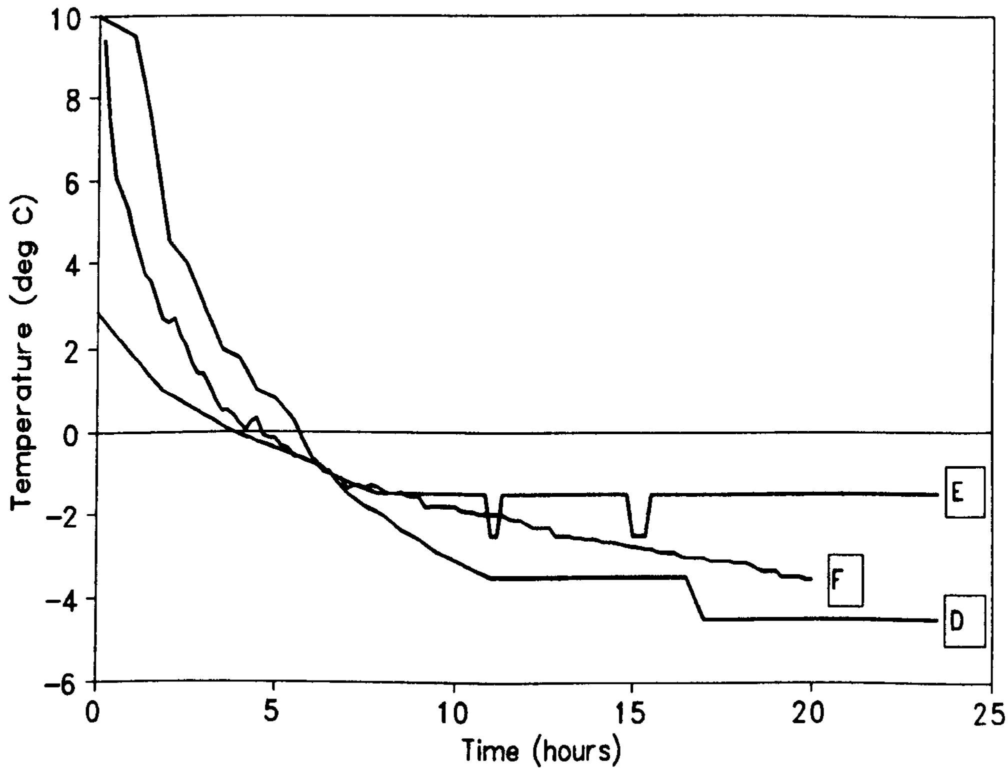

Figure 5.10 : Cooling profiles D, E and F

The second group of experiments was conducted to determine the influence of moisture migration on the initiation of needle-ice growth, and to enable the threshold conditions for ice segregation to be established. The soil surface was dried with a heat lamp and water added to the base of the sample, via a pipe placed down the side of the sample, until the bottom 1 cm of soil was saturated. Saturation was determined when the level of the water reservoir covered the bottom 1 cm of the soil. The soil was then cooled using profile D.

5.4 NEEDLE-ICE AND SOIL ANALYSIS

After each experiment the needle ice grown and any soil uplifted by the crystals was investigated using the methods described below.

5.4.1 Needle-ice analysis

Following each experiment details of the characteristics of the needle ice were recorded. First, the overall coverage of needle ice on the soil surface was mapped. The length of ten individual needles following detachment from the soil surface was then measured using vernier callipers. The needles were classified in terms of the presence or absence of a sediment load and whether material was incorporated into the needles or carried as a sediment cap.

After some of the experiments, sample of the ice and associated sediment were taken from a known area (determined by a template). These were weighed, dried at 105°C for 24 hours and then weighed again. Calculations were then made of the ice content (water equivalent) per unit area using the following expression

$$Y_i = \frac{(W_w - W_d)}{A} \tag{5.3}$$

Where Y_i is the weight of ice (g cm^{-2}), W_w and W_d the weights (g) of the 'wet' sample, dry sample, and A the area from which the sample was taken (cm^2).

The sediment load was calculated by

$$E=\frac{W_d}{A} \tag{5.4}$$

Where E is the amount of sediment lifted/incorporated (g cm^{-2}).

5.4.2 Soil analysis

Both the host material (the soil from the block) and included sediment (that which was incorporated and lifted by the ice) were analysed to determine their grain-size distribution, using the following method:

1) A sub-sample of the soil was taken for analysis of the organic matter content. This was ignited in a muffle furnace at 375°C for 24 hours.
2) The organic matter from the main sample was removed using hydrogen peroxide (so that the particles of organic matter were not included in the sieving).
3) The sample was wet-sieved through a 63μm sieve.
4) The proportion of the sample >63μm was wet-sieved through a bank of sieves at 0.5ϕ intervals - the coarsest being 2 mm.
5) The fine fraction (<63μm) was analysed using the pipette method (Akroyd, 1969; Head, 1980).

Grain-size analysis was also used to investigate whether the characteristics of the soil varied over the surface of samples USB_1 and DSB_1 after the run of experiments was completed. The surface of the block was divided into 16 squares of equal size (Figure 6.27). A sample of soil weighing 60 g to 100 g was taken from each square and analysed by the method described above.

5.5 EXPERIMENTAL DESIGN: SEDIMENT TRANSPORT EXPERIMENTS

A further series of experiments was conducted to investigate the processes and rates by which needle ice transports sediment downslope. The apparatus used for these experiments was modified from that described in Section 5.2 and is shown in Figure 5.11. Soil-moisture elements, platinum resistance thermometers and linear displacement transducers were used as shown in Figure 5.1. Both undisturbed and disturbed samples (USB_2 and DSB_2) were used to determine the effect of soil disturbance on the transport of material by needle ice.

The sample boxes (50 cm x 30 cm x 20 cm) were completely filled with either disturbed or undisturbed soil. The bases of the boxes were perforated and wicks (short lengths of string) were fed from the soil sample, through the holes and into a water reservoir (e.g. Higashi, 1958; Higashi and Corte, 1971). This provided a continuous supply of water to the sample and ensured that open system freezing occurred. Beneath the water reservoir there was a heating coil that prevented the water freezing. The apparatus was placed onto a wooden platform, one end of which was adjustable so that the platform could be tilted to produce different slope angles. To ensure that the displacement transducers rested parallel with the soil surface the stand onto which the transducer was clamped was also placed on the platform.

5.5.1 Introducing the marker particles into the soil surface

In many studies of soil erosion and sediment transport in varied environments, estimates of the rate of surface erosion have been made by repeatedly measuring markers placed on the soil surface. These markers include painted clasts, glass spheres, rock cubes, wooden pegs and metal discs (e.g. Brockie, 1968; Higashi and Corte, 1971; Van Steijn, 1977; Walton and Heilbronn, 1983; Pérez, 1987a,b,c, 1988). The rate of tracer movement is used to directly infer the rate of natural soil movement. The advantages of this method are that it is simple, inexpensive and can be easily replicated at different sites (Caine, 1981). However, the markers are often not

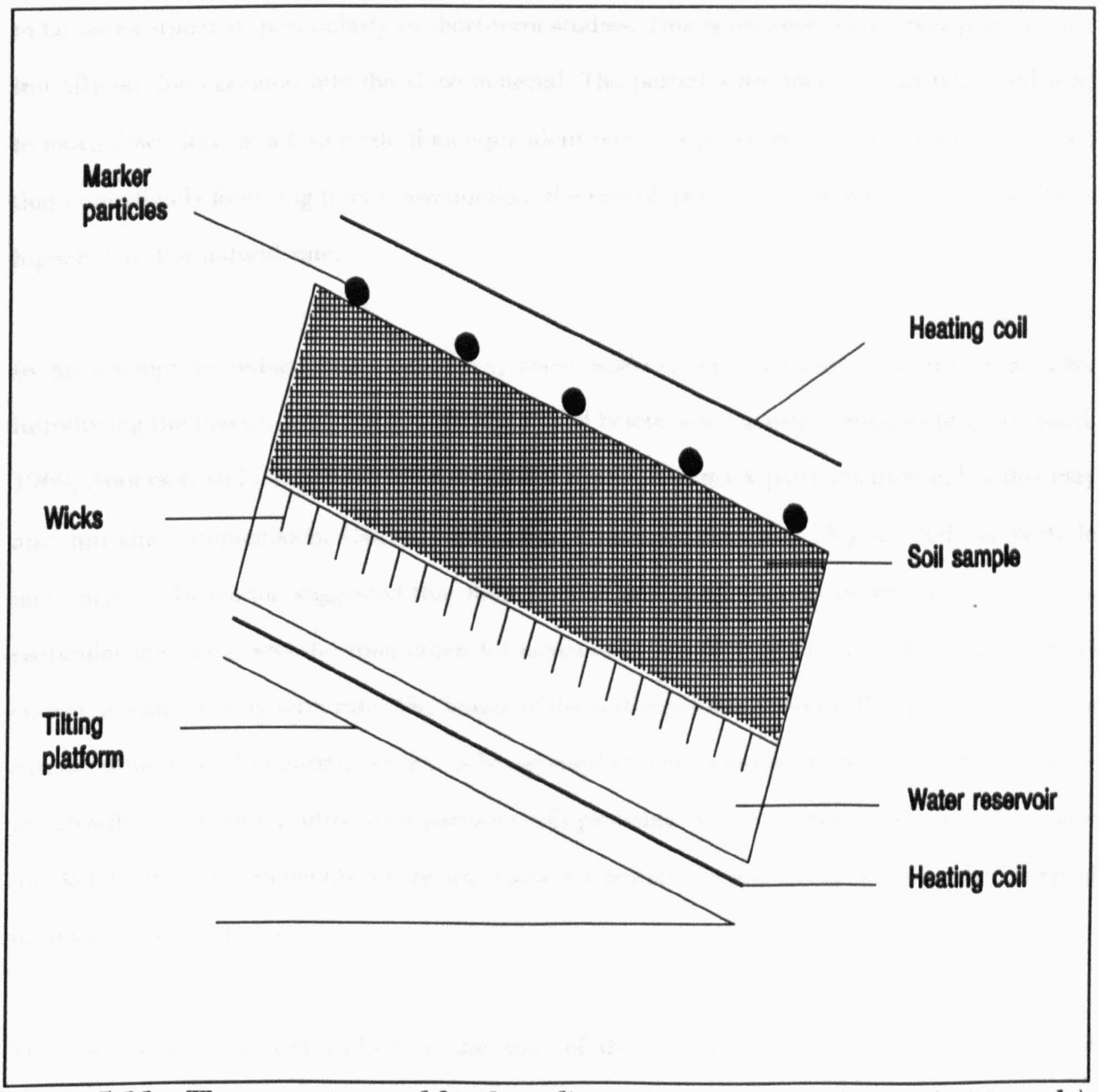

Figure 5.11 : The apparatus used for the sediment transport experiments (not to scale)

representative of the slope material on which they are used and thus may not give an accurate picture of the rate of particle movement.

Caine (1981), for example, argued that the use of markers causes the rate of sediment transport to be over-estimated, particularly in short-term studies. This is because the marker particles are initially not incorporated into the slope material. The particles are therefore unstable and tend to move downslope at a faster rate than equivalent particles in the natural soil. Caine suggested that immediately following tracer introduction, the rate of transport of the markers may be 300% higher than the natural rate.

In an attempt to reduce this inaccuracy, some workers have allowed a settling time after introducing the marker particles onto the slope and before starting measurements (e.g. Hayward, 1969; Anderson and Cox, 1978). The alternative to this is to mark particles in-situ, but this may also introduce imprecision. Caine (1981), from data collected in a 15-year study of particle movement in Tasmania, suggested that there should be a settling-down period of a year for his particular site, as it was the time taken for measured rates of introduced marker movement to converge with the long term rate. The length of the settling-down period will depend to a certain extent on the type of environment that is being studied. For example, in locations where needle-ice growth occurs daily, introduced particles will probably be incorporated into the soil surface quicker than in environments where the main mechanism of soil transport is by the creep of individual soil particles.

The condition of the soil surface at the start of the experiment also affects the amount of sediment transport. Pérez (1988) studied the effects of soil disturbance on the rates of clast movement. Clasts placed on the compacted plot initially moved quicker down the slope than clasts on the undisturbed plot. The effects of disturbance, however, did not last for a long period. Forty-seven days after the start of the experiment both the disturbed and undisturbed plots were covered by nubbins (small lumps of earth produced by needle-ice heave), and thus had similar surface characteristics. Pérez thus argued that maximum differences in particle transport between the disturbed and undisturbed plots should have existed immediately after particle seeding. After a short time the rates of movement on the smoothed plot converged with those on the undisturbed plot. This has important practical implications, and when investigating particle transport care should be taken not to alter soil-surface conditions (Pérez, 1988). Like Caine (1981) he also advised that there should be a settling down period after particles are put on the slope before measurements are taken.

In previous laboratory simulations of sediment by needle ice no settling period was allowed for, and measurements of particle movement were taken after the first freeze-thaw cycle. In this study two similar experiments were conducted to show how the distance of particle movement changed with successive freezing cycles, and to assess the length of the settling period required for the particles in the laboratory experiments.

For the first experiment stones were placed on the soil surface in a regular grid pattern and the sample was subjected to seven freeze-thaw cycles. After each thaw the locations of the particles were mapped (for method see Section 5.6). Figure 5.12 shows the rate of particle movement in each of the freezing cycles (each value represents the mean movement of 16 particles). To allow for differences in needle length between cycles the results are presented as the distance moved per unit length of ice crystal.

To determine whether introduced particles are transported at a different rate to in-situ 'incorporated' particles a comparison was made between the movement of 16 stones that had been on the soil surface for ten freeze-thaw cycles (which had been incorporated into the soil surface) and 16 stones which were newly placed on the soil surface. The sample was subjected to seven freeze-thaw cycles and the location of each particle measured after each thaw. The difference between the rate of particle movement of the 'introduced' and 'incorporated' clasts is shown in Figure 5.13.

Figure 5.12 shows that the rate of particle transport decreases from cycles one to four. After cycle four the rate of transport is similar in successive cycles. This pattern is also evident in Figure 5.13, whereby after four cycles there is a very small difference between the rates of movement of the 'introduced' and 'included' particles.

In the light of these results, and given the limited time for the experimental programme, once the particles were placed on the soil surface the soil was subjected to four freeze-thaw cycles before any measurements of particle movement were taken. Given a longer period for experimentation it is suggested that the samples should be subjected to at least seven freeze-thaw cycles before measurements are taken.

5.5.2 Types of marker particle

To monitor the movement of sediment downslope in this experiment four different types of marker were used:

i) spheres, with diameter 14 mm and 22 mm (Plate 5.5). Using spheres eliminates the possibility that differences in movement between the markers is a result of differences in their shape. Also, most other field and laboratory studies have used spheres as markers, thus, the results of these experiments should be comparable with the results of other studies. Two different size of particles were used to investigate whether particle size affects the distance of movement;

ii) cubes, with side-length 20 mm;

iii) stones, taken from the same location as the soil block, (mean a-axis length 20 mm, standard deviation 2.5 mm). A cross was drawn onto each stone so that the

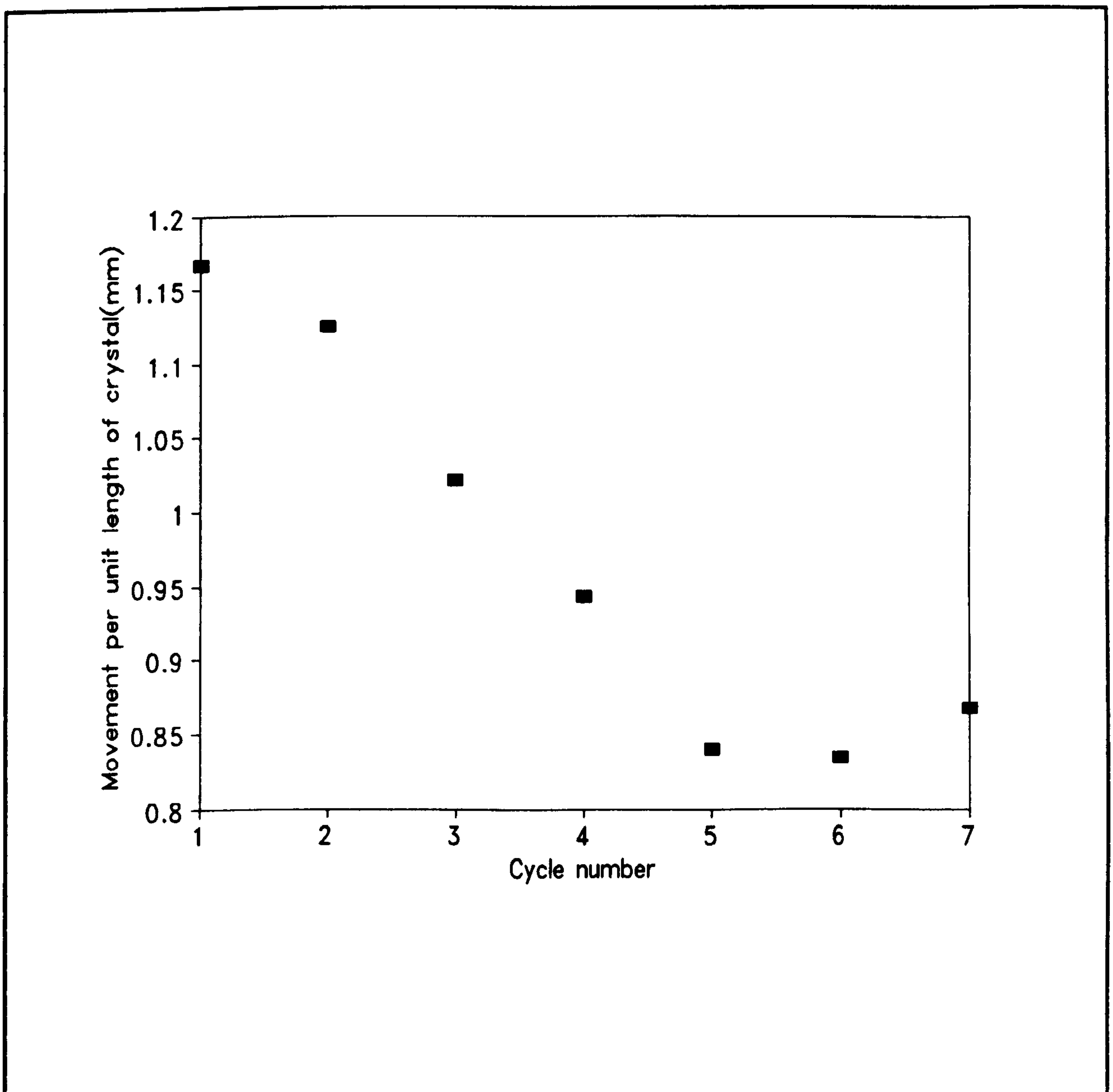

Figure 5.12 : Results of the experiment to determine the movement of particles with successive freezing cycles

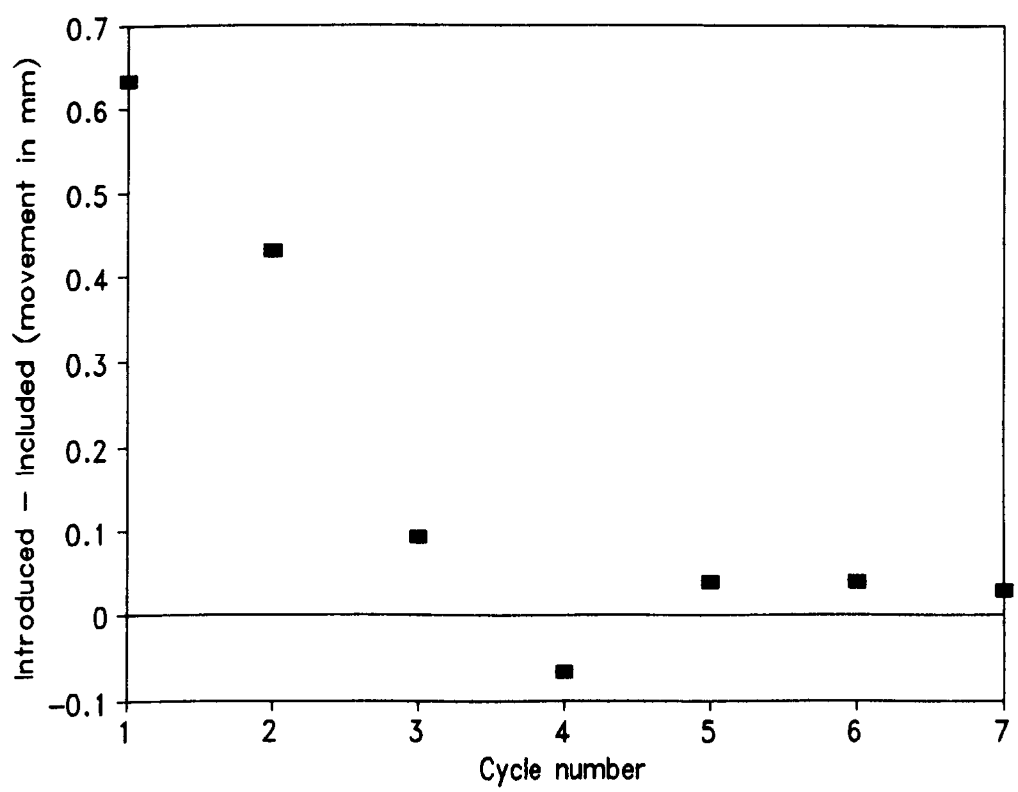

Figure 5.13 : Results of experiment to investigate the difference between the movement of introduced and incorporated particles. (Expressed in terms of movement per unit length of crystal.)

location of the stone could be measured with reference to the same point after each experiment. A problem with using stones, however, is that variations in their shape can cause them to be transported different distances under the same conditions. For example, round particles are more likely to roll than thin, flat particles;

iv) sand particles were also used to determine how smaller particles are transported. A template which had a regular grid of 20 square holes (each measuring 10 mm x 10 mm) cut into it was placed onto the soil surface. Sand was scattered evenly onto the template until the holes were covered with sand. The template was then removed, this left 20 squares of sand on the surface. The location of each square was measured with reference to its bottom right hand corner.

Squares of sand were also used in an attempt to show how particles incorporated within the needle-ice crystals are transported. The squares were produced as described above, then a layer of moist soil c.3 mm thick was put on top of the sand. The soil sample was then subjected to cooling profile E (Figure 5.10) so that monocyclic multitiered ice was produced (Sections 3.2.3b and 7.3.1). Particles were moved up to the soil surface as was evidenced by their appearance on the soil surface after the crystals melted. However, it was often difficult to determine which square or location within the square that the particles originated in. Thus, the experiments were not continued further, although this is a line of investigation which should be continued in the future (Section 10.2).

5.6 EXPERIMENTAL PROCEDURE: SEDIMENT TRANSPORT EXPERIMENTS

The transport experiments were carried out on six different slope angles (5, 6, 10, 15, 22 and 30°). Four to five experiments were conducted on each slope angle. Before the marker particles were placed onto the soil it was saturated with 1 litre of water and then left for four hours to equilibrate. The marker particles were placed onto the soil surface in a regular grid pattern (Plate 5.5) and the sample was subjected to four freeze-thaw cycles so that the particles were incorporated into the soil surface. The position of the particles on the soil surface was measured after the fourth cycle (see below). The sample was then subjected to cooling profile D (Figure 5.10).

After freezing, the cover of needle ice over the soil surface was mapped and the length of ten individual needles measured. The sample was then allowed to melt at room temperature. When the soil had thawed the position of the particles on the soil surface was mapped using a simple digitizing system (referenced to rulers on the side of the sample box) as illustrated in Figure 5.14. After the locations of the particles were measured the sample was frozen (with the same profile) and thawed for a further three to four times.

The locations of the particles were measured to within 0.25 mm. The accuracy of this technique was determined by randomly placing several particles on the soil surface, and comparing their mapped locations with a survey completed 24 hours later (care being taken to ensure that the samples remained undisturbed during this time). The error was the difference between the two sets of measurements. The mean difference between measurements was 0.018 mm (standard deviation 0.016 mm, n = 15).

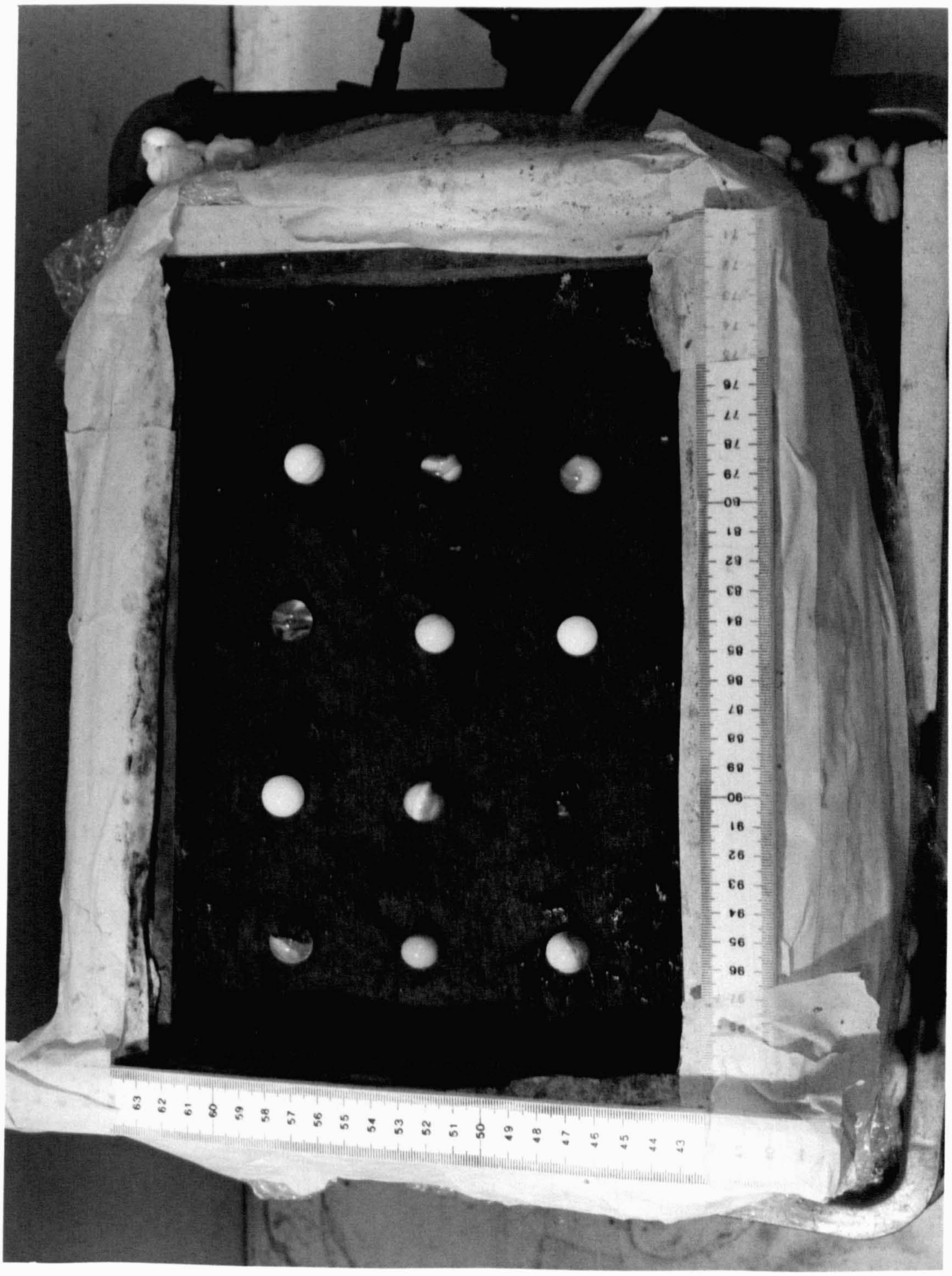

Plate 5.5 : Spheres on the soil surface

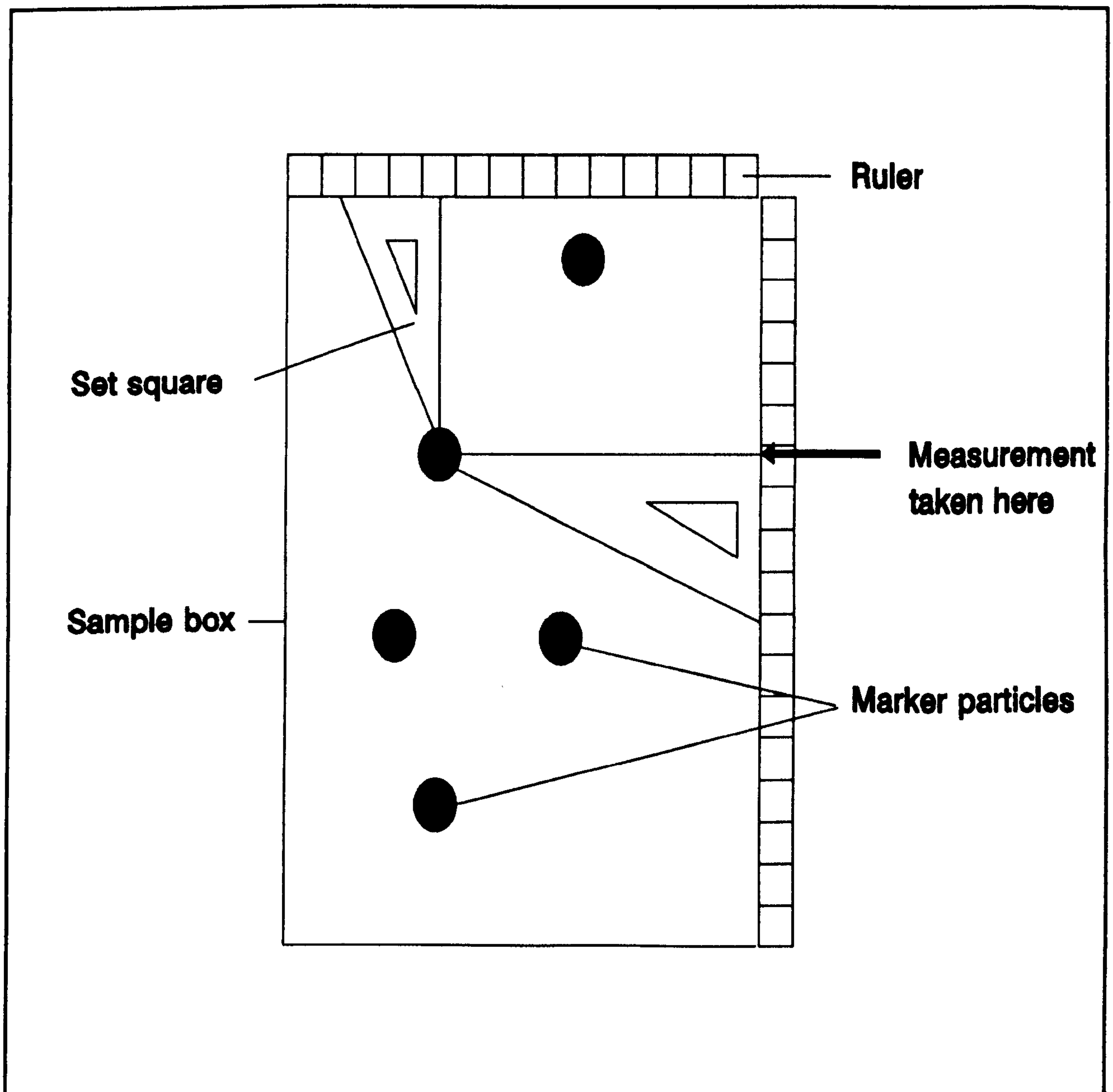

Figure 5.14 : The method by which the location of particles on the soil surface was measured

5.7 CONCLUSIONS

The experimental design used in this study attempted to build upon the type of apparatus used in the laboratory investigation of needle ice by other authors (Chapter 4). New types of automatic instrumentation have been incorporated into the experiment, e.g. soil-moisture elements and linear displacement transducers, which, when used with a datalogger, allowed the continuous measurement of soil-moisture content and soil heave. Soil-surface temperature was also automatically controlled using a microcomputer.

Unlike previous laboratory experiments both disturbed and undisturbed soil samples were used. This allowed the effect of soil disturbance on needle-ice growth and sediment erosion to be determined (Chapters 6,7 and 8).

A wider range of slope angles and marker particles than had previously been used were utilised in the sediment transport experiments. Before these experiments the marker particles were incorporated into the soil surface by subjecting the soil sample to several freeze-thaw cycles.

Chapter 6

THE PROCESS OF NEEDLE-ICE GROWTH AND GROWTH RATES

6.1 INTRODUCTION

6.1.1 Chapter structure

In this chapter results from the present series of laboratory experiments are discussed, with emphasis on the following:

i) case studies of an 'ideal' needle-ice growth event and a freezing cycle that did not produce needle ice;

ii) the controls of ice nucleation and ice segregation, in terms of soil-surface temperature, critical moisture content and moisture migration;

iii) the rate of needle-ice growth and the controlling factors;

iv) the spatial coverage of needle-ice growth on the soil surface.

Finally, conclusions from the whole series of experiments are discussed.

Part of the discussion is based on case studies of individual simulations; summaries of these, and all the other experiments, are presented in Appendix 4.

It was not possible to monitor moisture content continuously at the soil surface itself. Thus, most of the continuous moisture data presented here is from the element 1 cm below the soil surface (M_1), although this is thought to be representative of surface conditions.

The soil sample on which each experiment was carried out is indicated in the figure caption. T_s indicates soil-surface temperature, T_1, T_3 and T_5 represent the temperatures (°C) at 1, 3 and 5 cm below the soil surface and M_1, M_3, and M_5 the soil-moisture content (% dry weight) 1, 3, 5 and 10 cm below the soil surface as estimated from the soil-moisture element data. Needle-ice length (mm) is denoted by h. Where regression relationships are statistically significant at the 95% confidence level the regression line is drawn on the scatter plot.

In Sections 6.1.2 and 6.1.3, data from a typical 'ideal' needle-ice growth event and from a freezing event which did not produce needle ice are presented. This description forms the basis for the discussion in Section 6.2 where the controls of needle-ice growth in terms of soil-surface temperature and moisture content are investigated. These sections also raises issues which are then addressed in Section 6.2.

6.1.2 An ideal needle-ice event

Figure 6.1 shows the crystal length and soil-moisture content 1 cm below the soil surface from Experiment 21/3/91 and Figure 6.2 the temperature profile from this experiment. Needle-ice growth was almost continuous throughout the experiment (Figure 6.1). The profile of growth shows a pattern distinctive of 'normal' needle-ice growth, whereby the rate of growth is initially rapid (c.1.5 mm h^{-1} in the first 6 hours of growth) and then decreased (0.5 mm h^{-1} in hours 10 to 16 and 0.11 mm h^{-1} during hours 16 to 25).

The soil-moisture content decreased until hour 6 then increased until hour 12 to 13 before decreasing steadily until the end of the experiment. Whether the needle-ice growth forced the increase in moisture content or the increase in moisture caused needle-ice growth is an interesting question, and is discussed in the next section. The soil surface cooled slowly and temperatures in the soil profile (at T_1 and T_3) remained above 0°C (Figure 6.2); both of these conditions are necessary for needle-ice growth (Chapter 2).

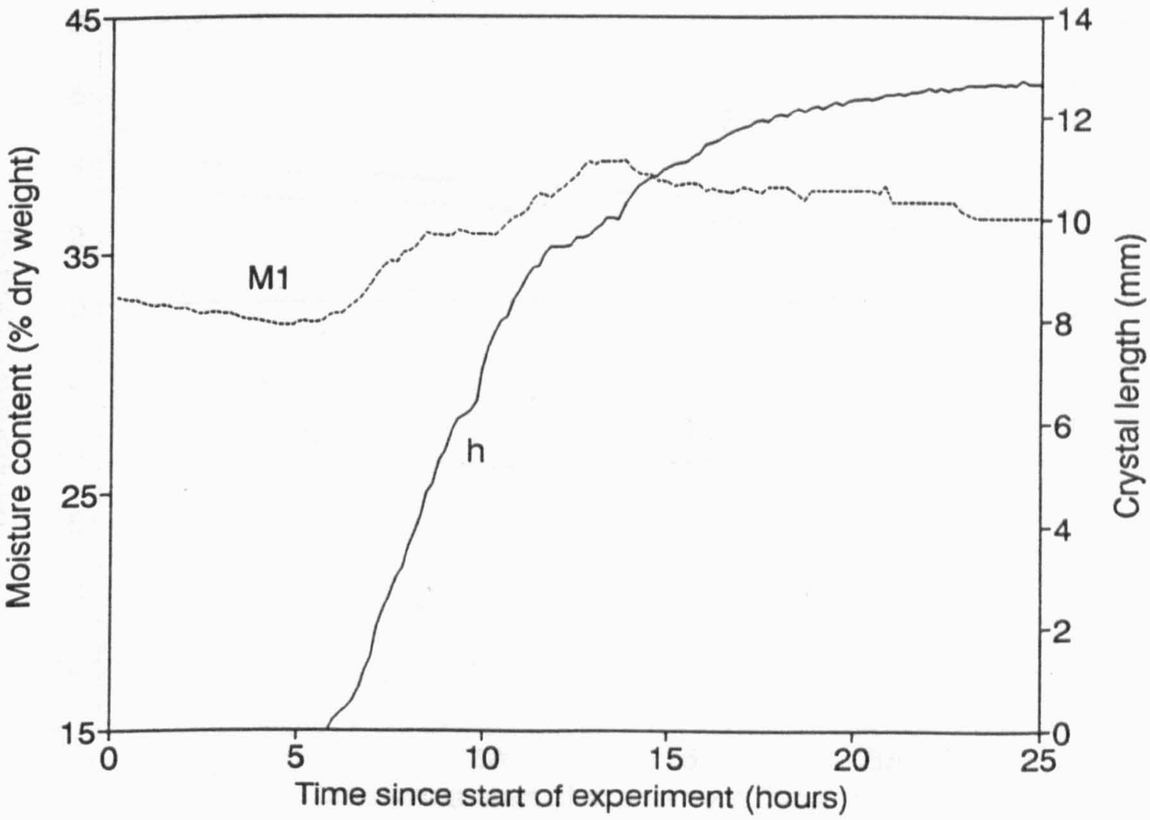

Figure 6.1 : Experiment 21/3/91; soil-moisture content and crystal length

USB$_1$

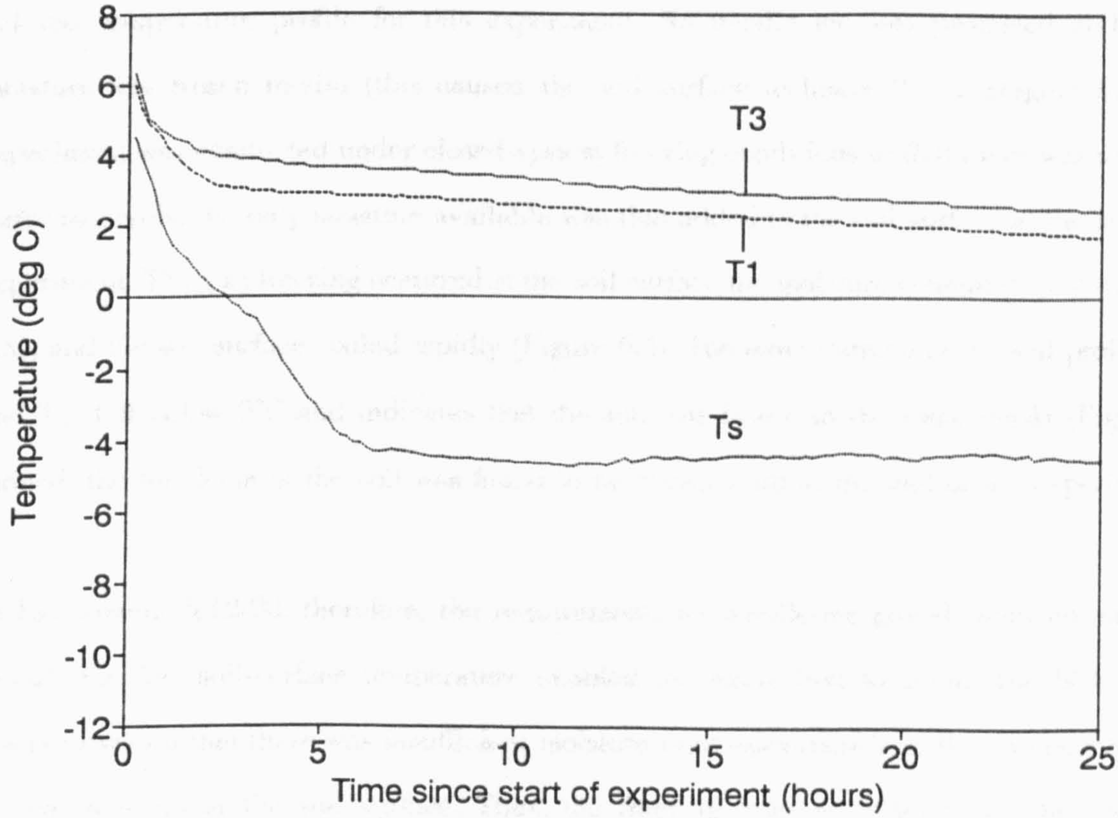

Figure 6.2 : Experiment 21/3/91; temperature profile **USB_1**

The conditions before and during needle-ice growth in this experiment fulfilled the requirements for growth outlined in Chapter 2, i.e. frost-susceptible soil, slow rate of soil surface cooling, soil-surface temperature low enough to initiate ice nucleation and a flow of moisture to the soil surface from further down in the soil profile.

6.1.3 Typical freezing event that did not produced needle ice

Figure 6.3 shows soil-moisture content and soil heave data for Experiment 5/12/90 and Figure 6.4 the temperature profile for this experiment. No needle ice was produced and the soil moisture was frozen in-situ (this caused the soil surface to heave 2 mm (Figure 6.3)). This experiment was conducted under closed-system freezing conditions in that there was no sub-soil water reservoir; the only moisture available was that added to the soil surface at the start of the experiment. Thus, as freezing occurred at the soil surface the moisture content decreased (Figure 6.3), and the soil surface cooled rapidly (Figure 6.4). The temperatures in the soil profile (at T_1 and T_3) fell below 0°C and indicates that the soil was frozen to the same depth (Figure 6.4): indeed, the top 5 cm of the soil was found to be frozen solid at the end of the experiment.

In Experiment 5/12/90, therefore, the requirements for needle-ice growth were not met. Even though the low soil-surface temperature enabled ice nucleation to occur, the lack of water reservoir meant that there was insufficient moisture (and associated heat flow) to match the rate of heat removal at the soil surface. Thus, the freezing front descended into the soil profile (Figure 6.4) and the soil moisture froze in-situ.

6.2 THE CONTROLS OF ICE NUCLEATION AND ICE SEGREGATION

In this section the influence of temperature and soil-moisture content on ice nucleation and needle-ice growth in the laboratory experiments, is discussed, with reference to the 'ideal' and

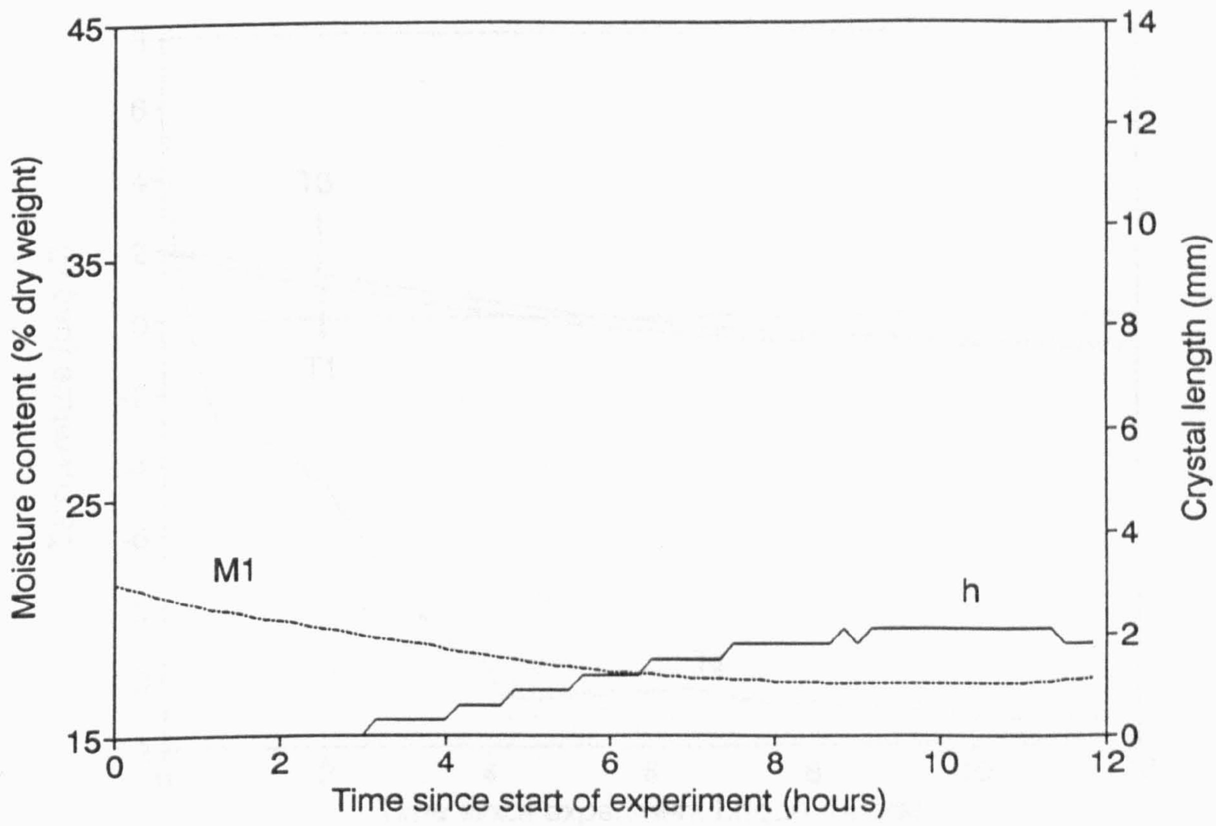

Figure 6.3 : Experiment 5/12/90; soil-moisture content and soil heave

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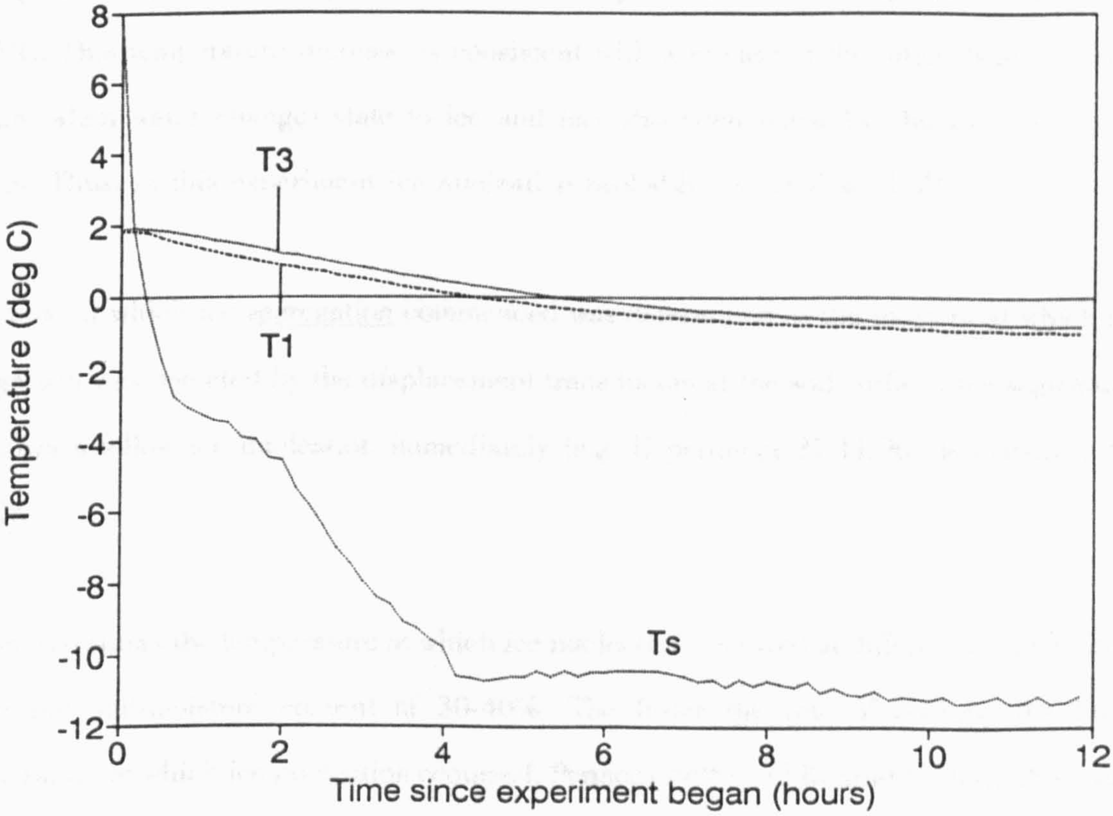

Figure 6.4 : Experiment 5/12/90; temperature profile **USB$_1$**

'non-ideal' events described above. Particular attention is paid to the interplay between soil-surface temperature and moisture content.

6.2.1 The control of ice nucleation by soil-surface cooling rate and moisture content

Ice nucleation (Section 2.3) is the point at which ice formation begins. In this series of experiments the ice was either pore ice or needle ice (Section 1.2.3). The moment at which ice nucleation occurred could usually be observed from the soil-surface temperature profile. For example, in Figure 6.5, at point A there is a rapid increase in temperature from -1.3°C to 0.05°C. This temperature increase is consistent with a release of the latent heat of fusion that occurs when water changes state to ice and has also been noted by Outcalt (1970a), among others. Thus, in this experiment ice nucleation probably occurred at -1.3°C.

The time at which ice segregation commenced was determined as the moment at which needle-ice growth was detected by the displacement transducers at the soil surface. Ice segregation did not always follow ice nucleation immediately (e.g. Experiment 27/11/90, described in Section 6.2.3a).

Figure 6.6 shows the temperature at which ice nucleation occurred at different cooling rates, with an initial soil-moisture content of 30-40%. The faster the rate of cooling, the lower the temperature at which ice nucleation occurred. Penner (1986) and Konrad (1989), who conducted soil freezing experiments with slower rates of cooling than the present study, also found that the temperatures at which ice-lens growth commenced and stopped decreased as the rate of cooling increased.

The temperature at which ice nucleation occurred was also influenced by the soil-moisture content. In soils with a high soil-moisture content (60-70%) a lower air temperature (below -5°C) was needed to freeze the soil than was required to freeze soils with a moisture content 25-35%

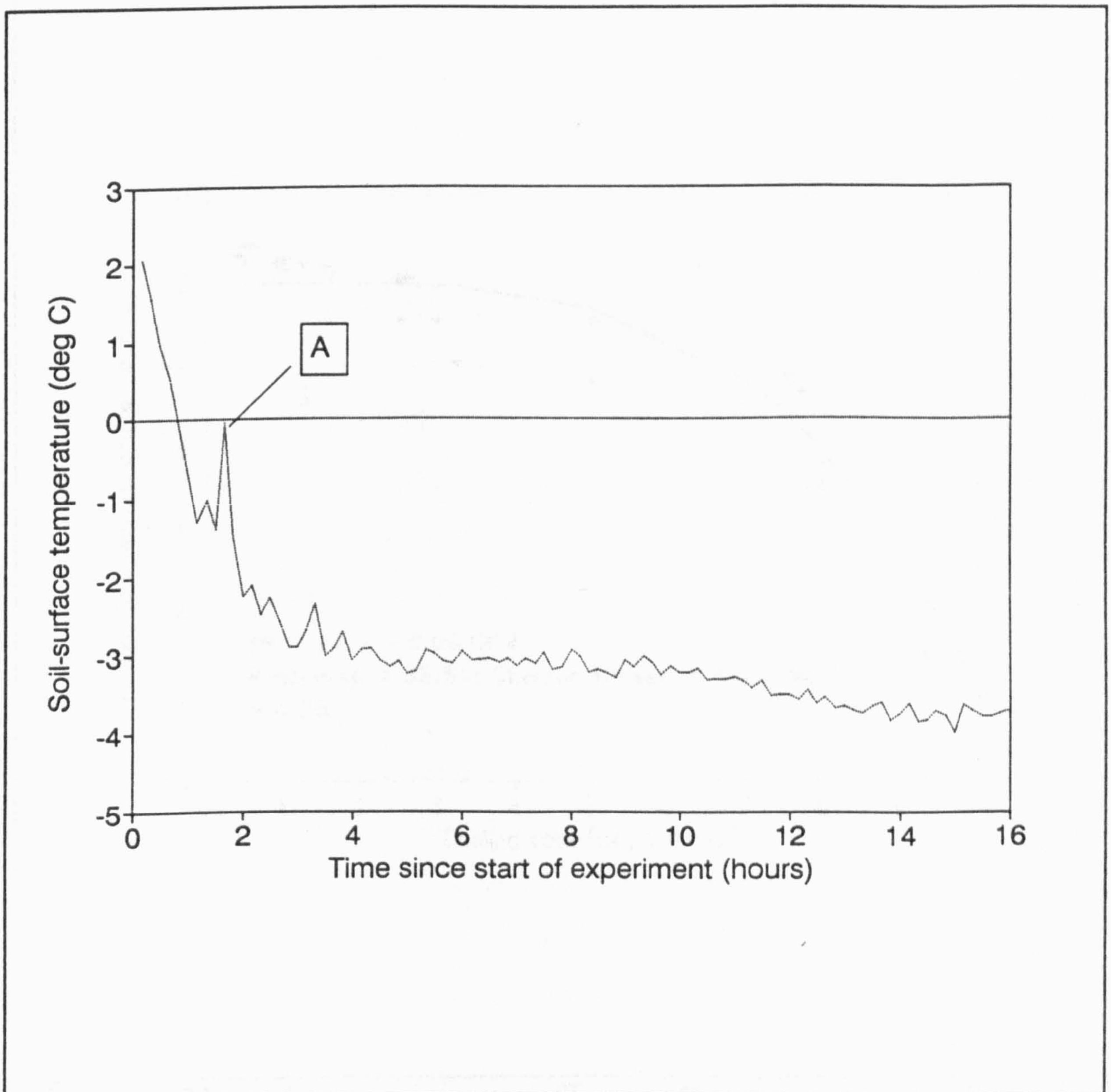

Figure 6.5 : Experiment 10/1/90; soil-surface temperature **DSE_1**

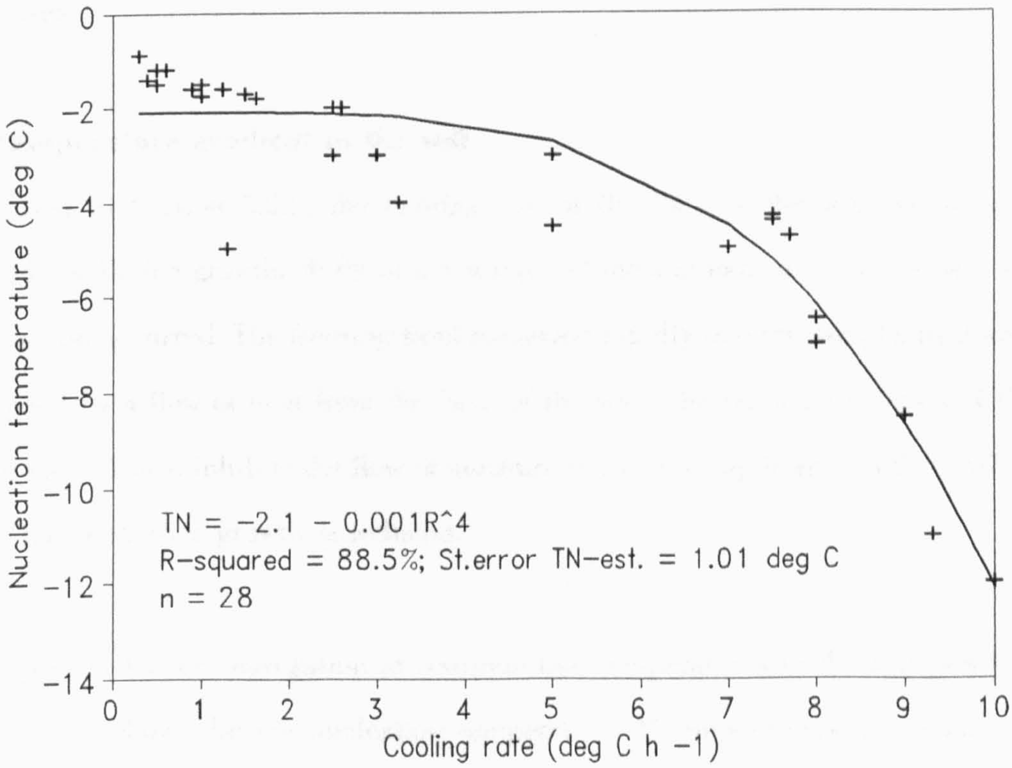

Figure 6.6 : The nucleation temperature (T_N) at different cooling rates (R)

USB_1 and USB_2, 30 to 40% soil-moisture content

(-0.5 to -3°C). With a high moisture content the soil has a greater diffusivity and heat can easily be withdrawn from the surrounding soil (Section 2.3.2e). Given this, a low air temperature is necessary to remove enough heat from the water to cool the soil surface to the nucleation temperature. For soils with less than c.10% soil-moisture content, however, temperatures lower than -10°C were required to cause ice nucleation (e.g. Figures 6.3 and 6.4). This is arguably because there is only a limited amount of water available to be frozen and often the water in the adsorbed layer (Figure 2.6) of the soil particle is frozen, which only occurs at very low temperatures.

6.2.2 Temperature gradient in the soil

As suggested in Section 5.2.2, the heating coil at the base of the soil sample (Figure 5.1) influenced needle-ice growth. Without a heating coil the soil moisture froze in-situ and thus no ice segregation occurred. The freezing front advanced rapidly into the sample, as it was probably not balanced by a flow of heat from the base of the soil. The rapid penetration of the freezing front into the soil also inhibits the flow of moisture to the freezing front (Smith, 1987). Thus, the potential for needle-ice growth is reduced.

It was important for ice segregation to continue that temperatures in the soil profile (i.e. at T_1 and T_3) stayed above the ice nucleation temperature. If temperatures fell below this critical threshold then ice nucleation occurred below the soil surface and the freezing front descended into the soil profile, and ice segregation ceased. An example of this is shown in Figure 6.7; needle-ice growth ceased at point A when the temperature 1 cm below the soil surface fell to -0.2°C.

Conversely, if too <u>much</u> heat was supplied to the base of the soil, needle-ice growth was also prevented (e.g. Figure 6.8). This was exacerbated by a high soil thermal conductivity. As a

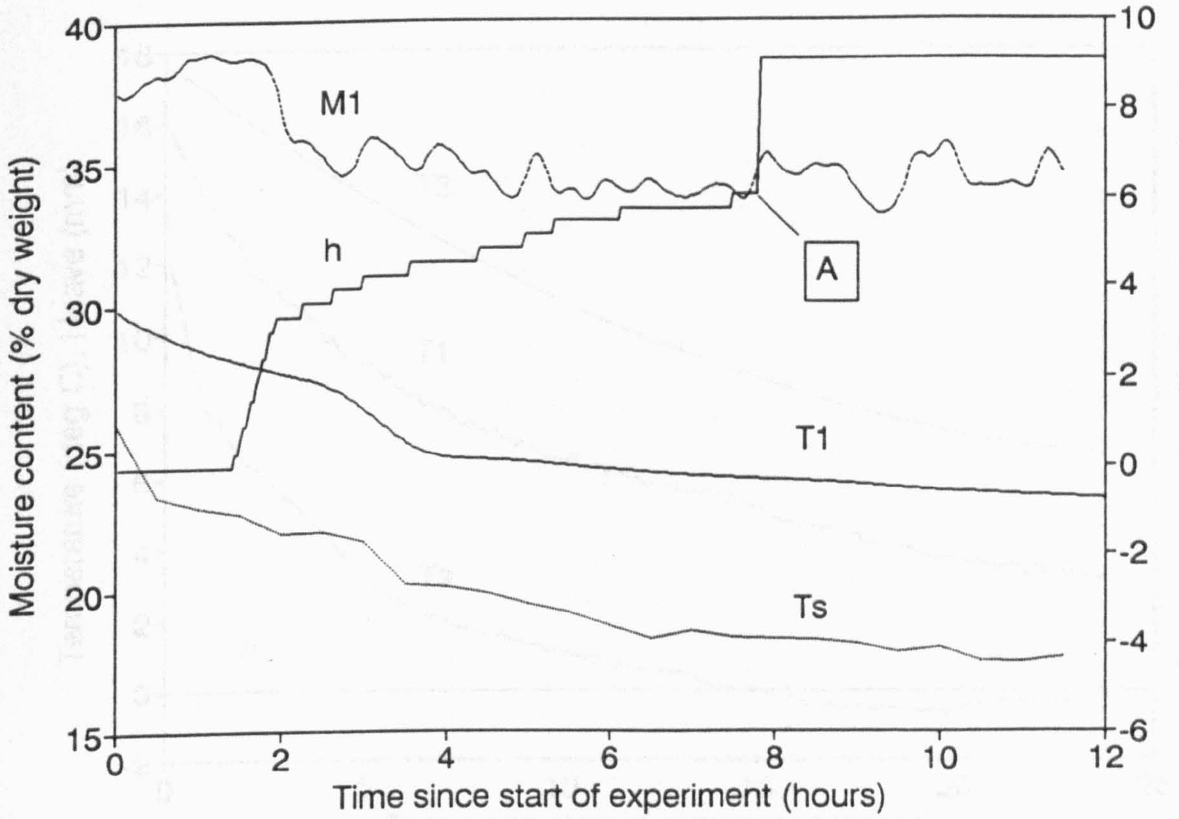

Figure 6.7 : Experiment 9/7/91; temperature, soil-moisture content and crystal length

USB$_1$

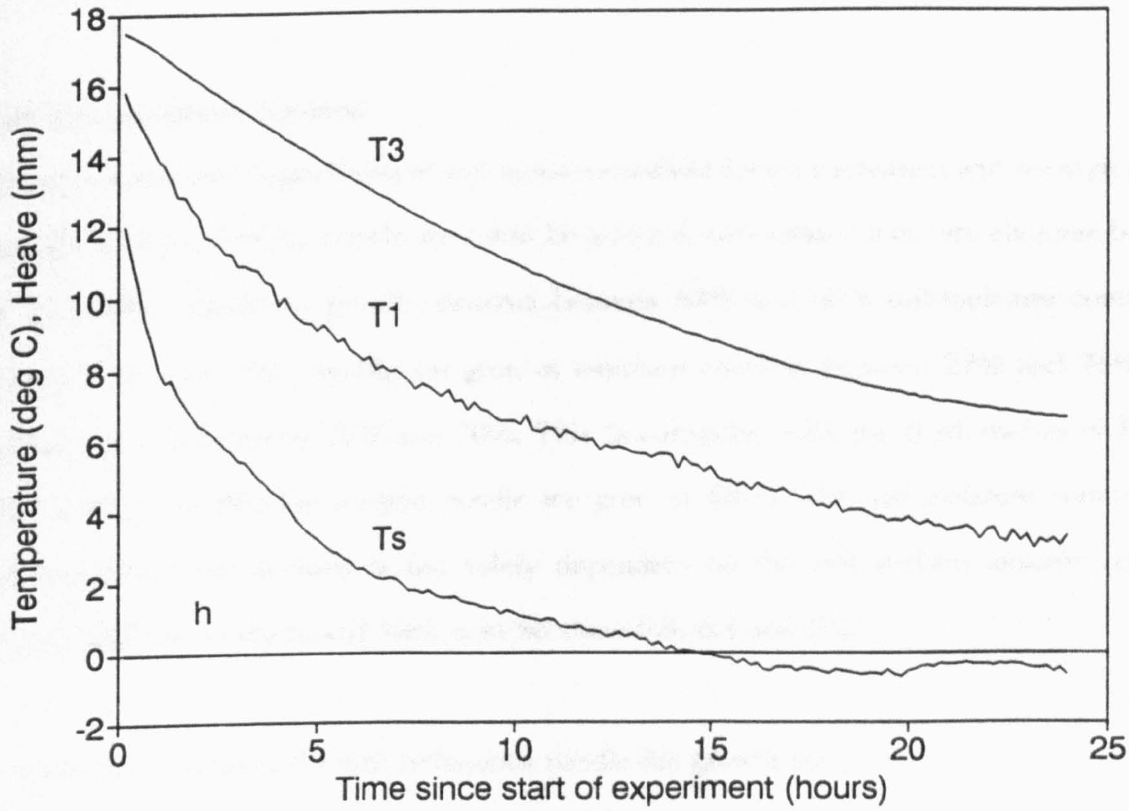

Figure 6.8 : Experiment P3; temperature and soil heave DSE$_1$

result, a low air temperature was required to remove sufficient heat from the soil surface before freezing could occur.

The temperature gradient in the soil is also important in that it may initiate a flux of soil moisture (e.g. Williams and Smith, 1989). It is generally thought that moisture flows from warm areas to cold areas (i.e towards the soil surface, Section 2.4.3). Thus, when there was a water reservoir, moisture was usually drawn to the soil surface. This is discussed further in the following section.

6.2.3 Soil-moisture content

There were lower and upper limits of soil-moisture content for ice nucleation and ice segregation. In sample DSE_1 and DSB_1 needle ice could be grown at soil-surface moisture contents between 23% and 70%. Maximum growth occurred between 60% and 65% soil-moisture content. In samples USB_1 and USB_2 needle ice grew at moisture contents between 27% and 76%, with maximum growth between 55% and 70%. This is consistent with the field studies of Fukuda (1936) who found that the longest needle ice grew at 60 to 70% soil-moisture content. The length of needle-ice crystals is not solely dependent on the soil surface moisture content, however, and this is discussed further in Sections 6.3, 6.4 and 9.2.

The moisture content of the soil influences needle-ice growth by:

i) providing a water supply to 'feed' growing ice crystals;

ii) affecting the thermal diffusivity of the soil (Section 2.3.2e), and thus how quickly the soil temperature changes in response to changes in air temperature;

iii) migrating to the soil surface and carrying heat from warmer regions lower down in the soil profile. Thus, moisture can provide a source of heat to the freezing front.

6.2.3a The lower limit of soil-moisture content. No needle ice was produced in any soil with soil-moisture contents lower than 23%, and below this value the moisture froze in-situ. Low matric potentials develop in dry soil and produce a reverse hydraulic gradient (Section 2.4.3), which inhibits flow of water to the freezing front. Also, at low soil-moisture contents the soil surface cools quickly (Section 6.2.5).

An example serves to illustrate these effects. Before Experiment 10/1/90, the soil surface was dried for four hours using a heat lamp. The moisture content at the soil surface prior to cooling was 13.4%. Figure 6.9 shows soil-surface temperature and soil-moisture content during this experiment. Within half an hour of the start of the experiment, cooling seemed to produce tension at the soil surface and moisture was drawn towards the colder soil surface, this is evidenced by an increase in the moisture content at element M_1. At element M_3 there was no significant increase in soil moisture content until 3.8 hours into the experiment. This was shortly after ice nucleation occurred at the soil surface (point A). It is suggested that the increase of moisture content at element M_1 and M_3 was initiated by the tension caused by ice nucleation.

At element M_1 the moisture content increased at an average rate of c.0.75% h^{-1} over 18 hours. Ice nucleation did not cause a rapid increase in moisture content here because this area of the soil was frozen immediately after ice nucleation. By the end of the experiment the moisture content was 28%, which, combined with the soil-surface temperature of -4°C, was insufficient for ice segregation to occur. The top few millimetres of the soil were frozen in-situ.

In some experiments ice segregation did not occur until sufficient moisture had migrated to the soil surface. For example, before Experiment 27/11/90 (Figure 6.10), the soil surface was dried with a lamp until the soil-moisture content was 15%. The sample was then cooled. Initially the soil-moisture content near the surface decreased. This may have been due to some residual warmth in the soil, encouraging high evaporation rates at the start of the experiment (for

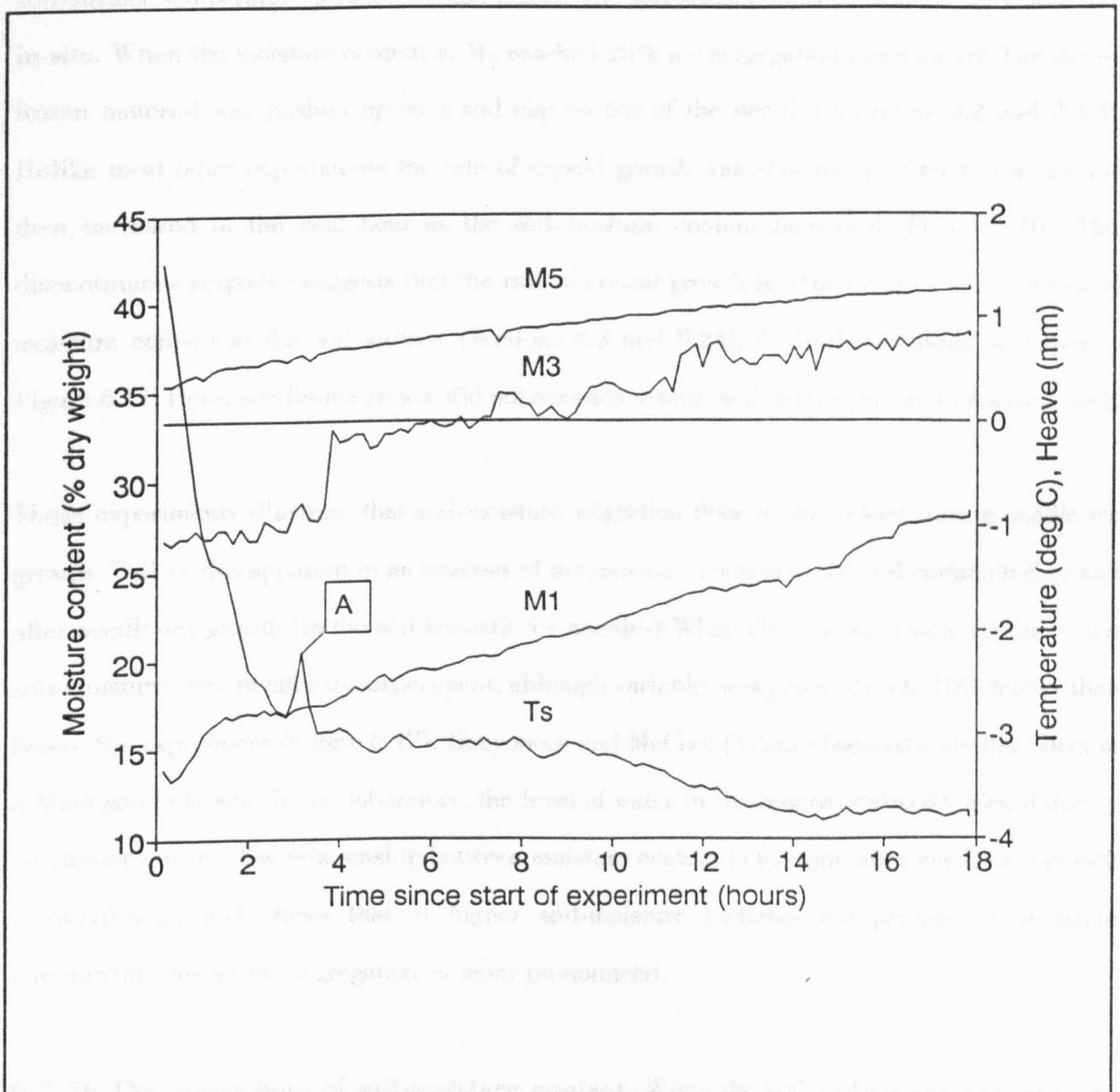

Figure 6.9 : Experiment 10/1/90; soil-surface temperature and soil-moisture content **DSE_1**

subsequent experiments the sample was left to cool overnight before it was frozen). As cooling progressed, however, additional water appeared to be 'pulled' towards the soil surface (Figure 6.10). After 7.5 h the nucleation temperature was reached, indicated by a slight 'bump' in the soil-surface temperature profile (Section 6.2.1). The soil-surface moisture then seemed to freeze in-situ. When the moisture content at M_1 reached 28% ice segregation commenced. The in-situ frozen material was pushed up as a soil cap on top of the needles (Sections 3.2 and 7.3.3). Unlike most other experiments the rate of crystal growth was slow for the first two hours and then increased in the next hour as the soil-moisture content increased (Figure 6.10). This discontinuous response suggests that the rate of crystal growth is dependent on some threshold moisture content at the soil surface (Sections 6.3 and 9.24). A similar example is shown in Figure 6.11. Here, needle-ice growth did not commence until soil-moisture content reached 36%.

These experiments illustrate that soil-moisture migration does occur indeed during needle-ice growth. This is also apparent in an analysis of the moisture content at the soil surface before and after needle-ice growth (in the soil beneath the needles). When clear needles were produced the soil-moisture content after the experiment, although variable, was generally 5 to 10% higher than before the experiment (Figure 6.12). Bouyoucos and McCool (1928) observed a similar effect at a Michigan field site. In the laboratory, the level of water in the reservoir also decreased during needle-ice growth. The relationship between moisture content before and after needle-ice growth is curvilinear, and shows that at higher soil-moisture contents the process of 'moisture enrichment' due to ice segregation is more pronounced.

6.2.3b The upper limit of soil-moisture content. When the soil surface was first saturated by pouring water onto the soil until no more could be absorbed (and a film of water covered the soil surface, above c.76% soil-moisture content) ice segregation did not occur during subsequent freezing experiments. Here, the thermal conductivity of the upper layers of soil was high. This seemed to induce a significantly high flow of heat to the soil surface to prevent cold

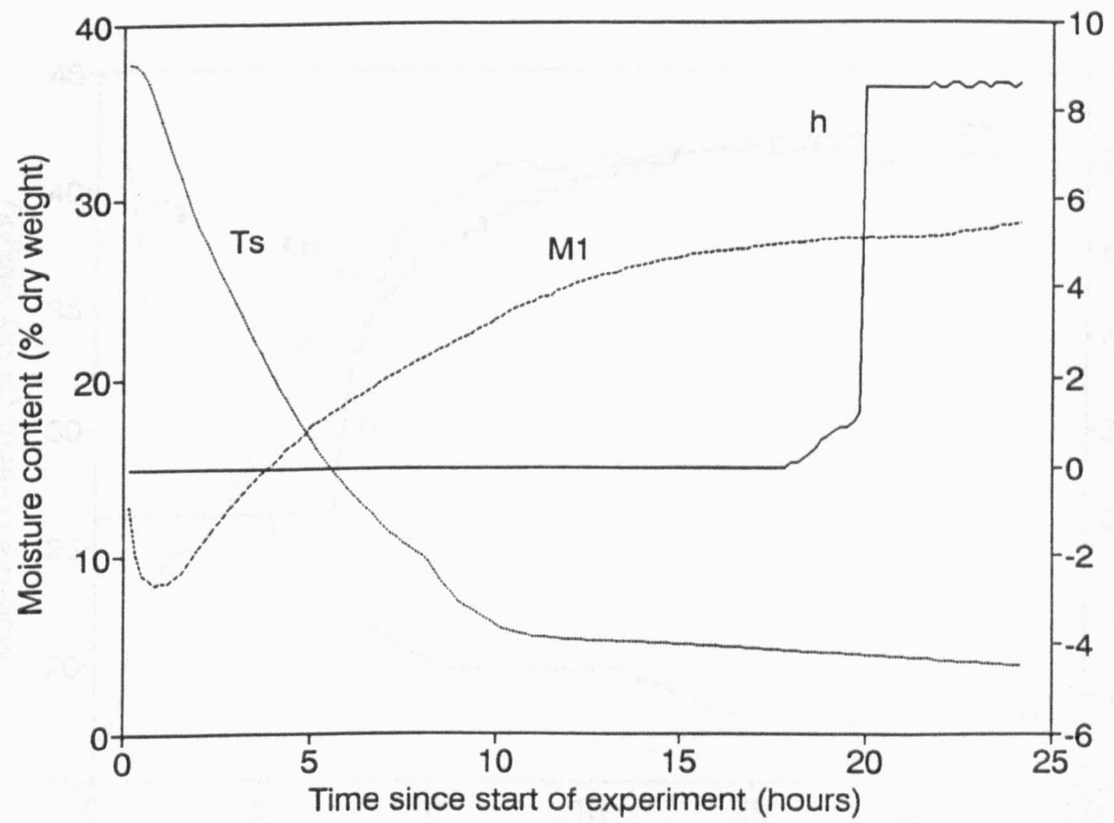

Figure 6.10 : Experiment 27/11/90; soil-surface temperature, moisture content and needle-ice length **USB_1**

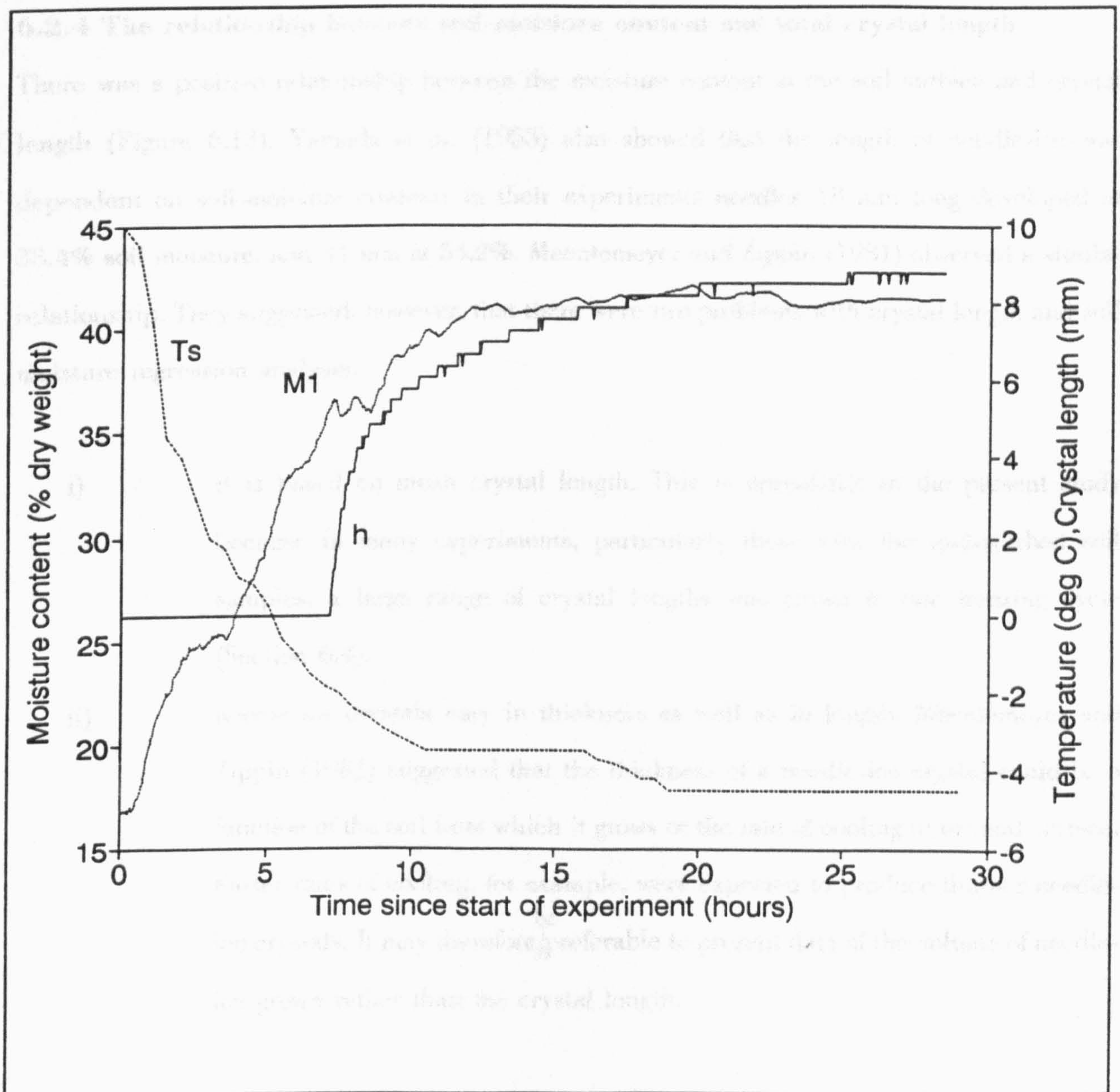

Figure 6.11 : Experiment 3/7/91; soil moisture content, soil-surface temperature and needle-ice growth **USB$_1$**

temperatures from penetrating into the sample. At soil-surface temperatures lower than c.-10°C the film of water froze and produced a thin layer of ice at the soil surface. This frozen layer appeared to insulate the soil surface from further changes in temperature.

6.2.4 The relationship between soil-moisture content and total crystal length

There was a positive relationship between the moisture content at the soil surface and crystal length (Figure 6.13). Yamada *et al.* (1955) also showed that the length of needle-ice was dependent on soil-moisture content: in their experiments needles 18 mm long developed at 35.4% soil moisture, and 31 mm at 53.2%. Meentemeyer and Zippin (1981) observed a similar relationship. They suggested, however, that there were two problems with crystal length and soil moisture regression analysis:

i) it is based on mean crystal length. This is unrealistic in the present study because in many experiments, particularly those with the undisturbed soil samples, a large range of crystal lengths was grown in one freezing cycle (Section 6.4);

ii) needle-ice crystals vary in thickness as well as in length. Meentemeyer and Zippin (1981) suggested that the thickness of a needle-ice crystal could be a function of the soil from which it grows or the rate of cooling of the soil surface. Faster rates of cooling, for example, were expected to produce thinner needle-ice crystals. It may therefore be preferable to present data of the volume of needle-ice grown rather than the crystal length.

Additionally, Beskow (1935) and Fukuda (1936) stated that needle-ice crystals were thicker at their bases. It may be more appropriate, therefore, to relate the volume of needle ice grown (rather than the crystal length) with the controlling variables.

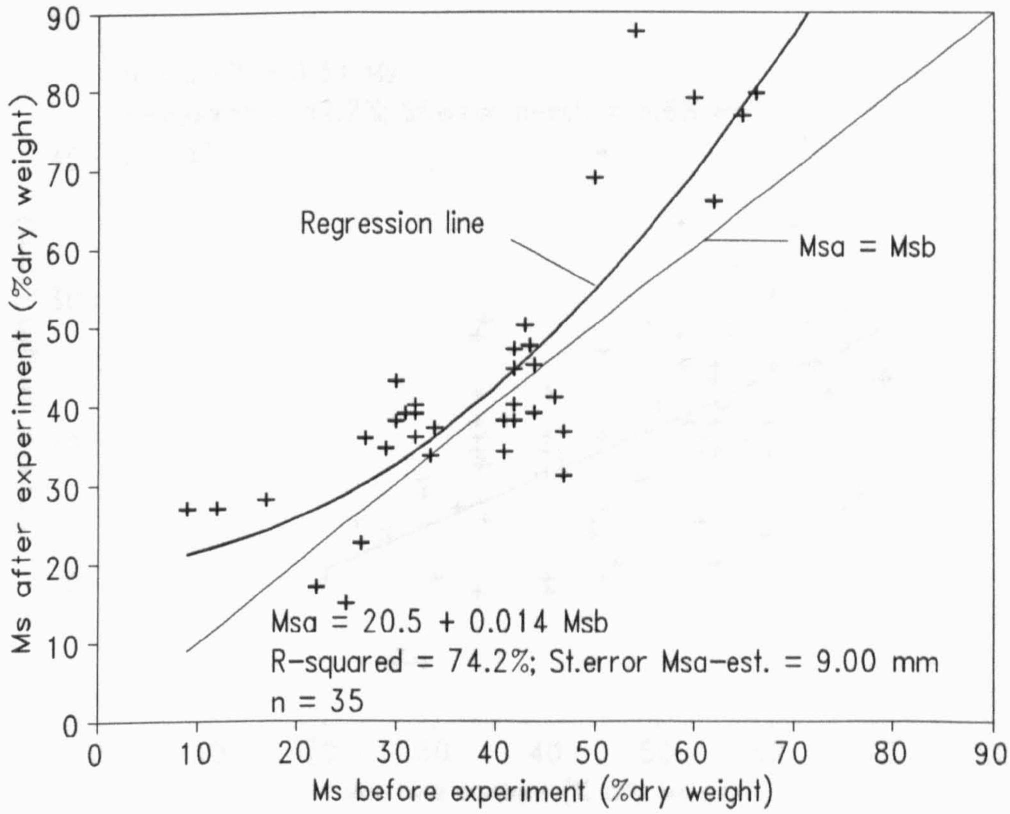

Figure 6.12 : Soil surface moisture content before (M_{sb}) and after (M_{sa}) needle-ice growth **USB_1**

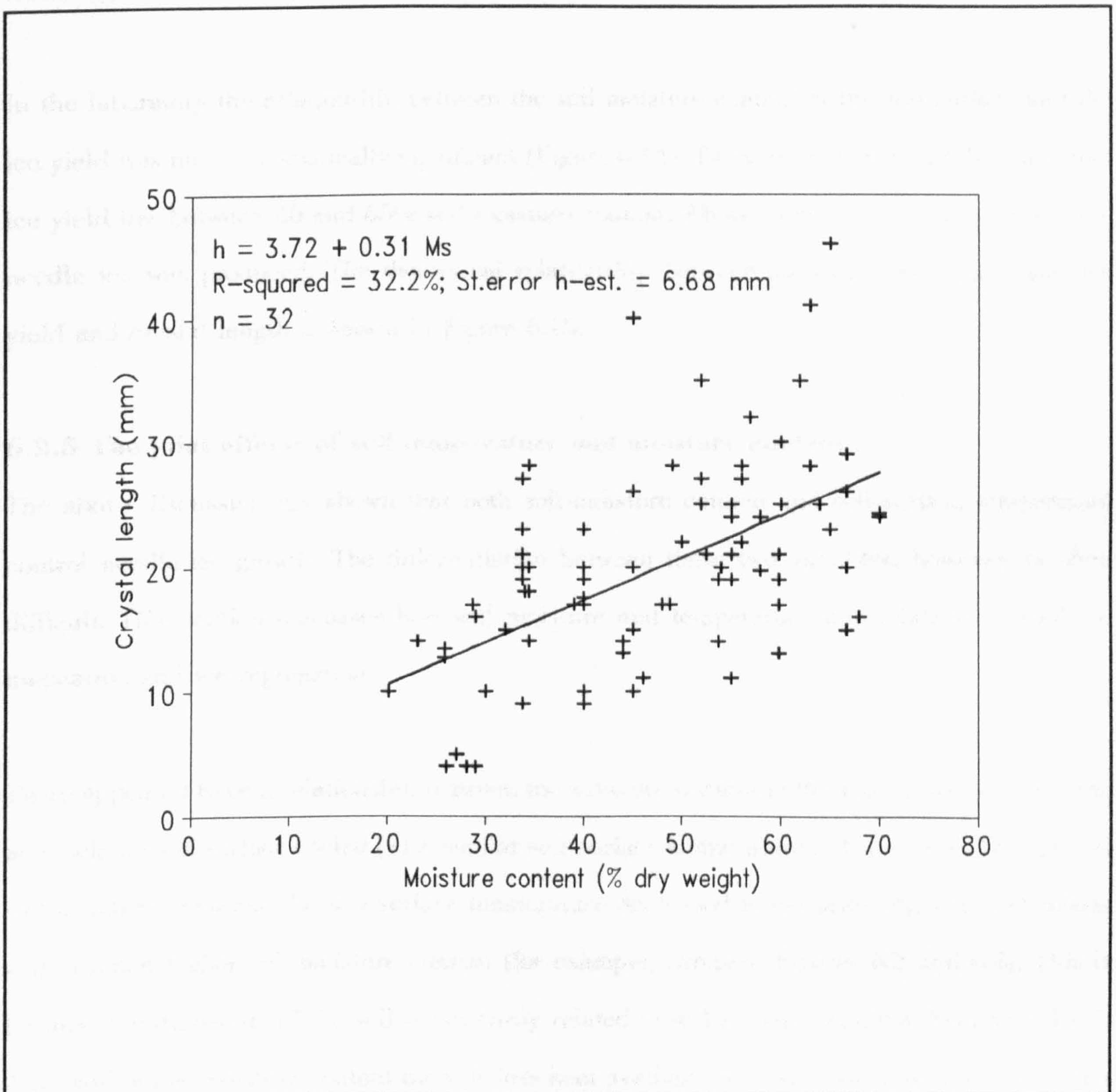

Figure 6.13 : The relationship between soil-moisture content and crystal length

USB_1

There is considerable scatter of the moisture content/crystal length relationship, illustrated by the high value of the standard error (Figure 6.13). This suggests that other factors also influence the length of needle ice, such as the rate of cooling and duration of sub-freezing temperatures following nucleation. These are discussed in Section 9.2.

In the laboratory the relationship between the soil moisture content at the soil surface and the ice yield was not statistically significant (Figure 6.14). There is evidence that the maximum ice yield lies between 60 and 65% soil-moisture content. Above 76% soil-moisture content no needle ice was produced. The theoretical relationship between soil-moisture content and ice yield and crystal length is shown in Figure 6.15.

6.2.5 The joint effects of soil temperature and moisture content

The above discussion has shown that both soil-moisture content and soil-surface temperature control needle-ice growth. The differentiation between these two variables, however, is often difficult. This section discusses how soil moisture and temperature interrelate to control ice nucleation and ice segregation.

There appeared to be a relationship between the moisture content at the soil surface and the rate at which the soil surface cooled (with similar soil-surface temperatures). In experiments with low soil-moisture contents, the soil-surface temperature decreased much faster than in simulations with a much higher soil-moisture content (for example, compare Figures 6.2 and 6.4). This is because the diffusivity of the soil is positively related to soil-moisture content (Section 2.3.2e). Also, with a low moisture content there is less heat available from both the latent heat of fusion and the heat transported in the moisture from lower in the soil profile. Thus, there is only a limited amount of heat available to replace that which is lost at the soil surface by cooling. At low soil-moisture contents (c.5 to 35%) it was difficult to obtain a slow rate of surface cooling. The actual cooling curves were thus different from those stipulated in the computer programmes.

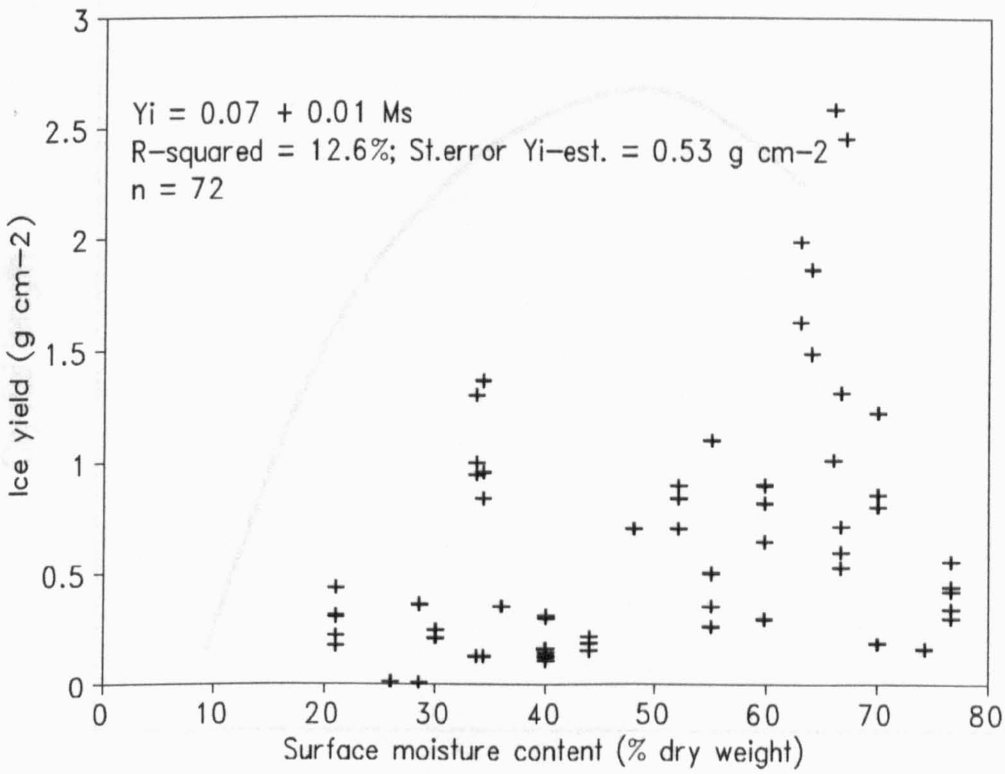

Figure 6.14 : The relationship between soil-moisture content and ice yield (Y_i)

USB_1

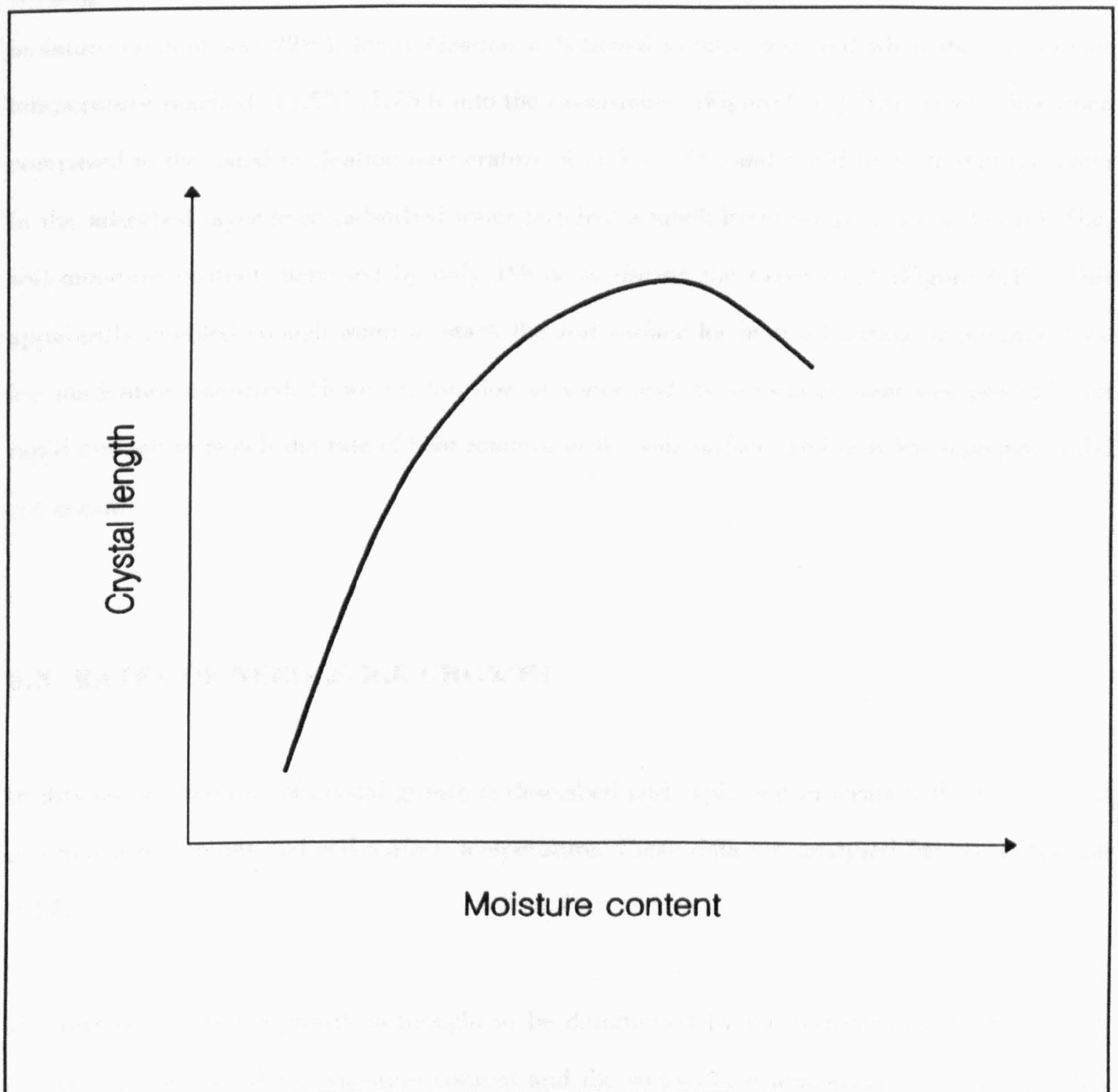

Figure 6.15 : The theoretical relationship between soil moisture content and ice yield and crystal length

A typical example is shown in Figure 6.16.

Prior to Experiment 4/12/90 (Figure 6.17) the soil surface was dried with a heat lamp before cooling. The moisture content of the surface soil after drying was 3% (although at M_1 the moisture content was 22%). Ice nucleation is believed to have occurred when the soil-surface temperature reached -11.5°C (1.75 h into the experiment) (Figure 6.17). This is very low when compared to the usual nucleation temperature of -1.5 to -3°C, and could indicate that the water in the adsorbed layer froze (adsorbed water requires a much lower temperature to freeze). The soil-moisture content increased by only 1% or so during the experiment (Figure 6.17). This apparently enabled enough water to reach the soil surface for in-situ freezing to continue once ice nucleation occurred. However, the flow of water and its associated heat was probably not rapid enough to match the rate of heat removal at the soil surface, and thus ice segregation did not occur.

6.3 RATES OF NEEDLE-ICE GROWTH

In this section the rate of crystal growth is described and explained in terms of the influence of soil-moisture content and soil-surface temperature. These data are analysed further in Section 9.2.3.

The rate of needle-ice growth is thought to be determined by the transfer of heat in the soil, which is a function of soil-moisture content and the soil-surface temperature (Section 2.2.2a). As long as the freezing front is stable, needle ice grows (Section 2.5). Fujita (1936) stated that the rate of needle-ice growth is controlled by the availability of water at the freezing front. He also noted that a steep temperature gradient in the soil will increase the rate of needle-ice growth (as long as there is sufficient moisture available).

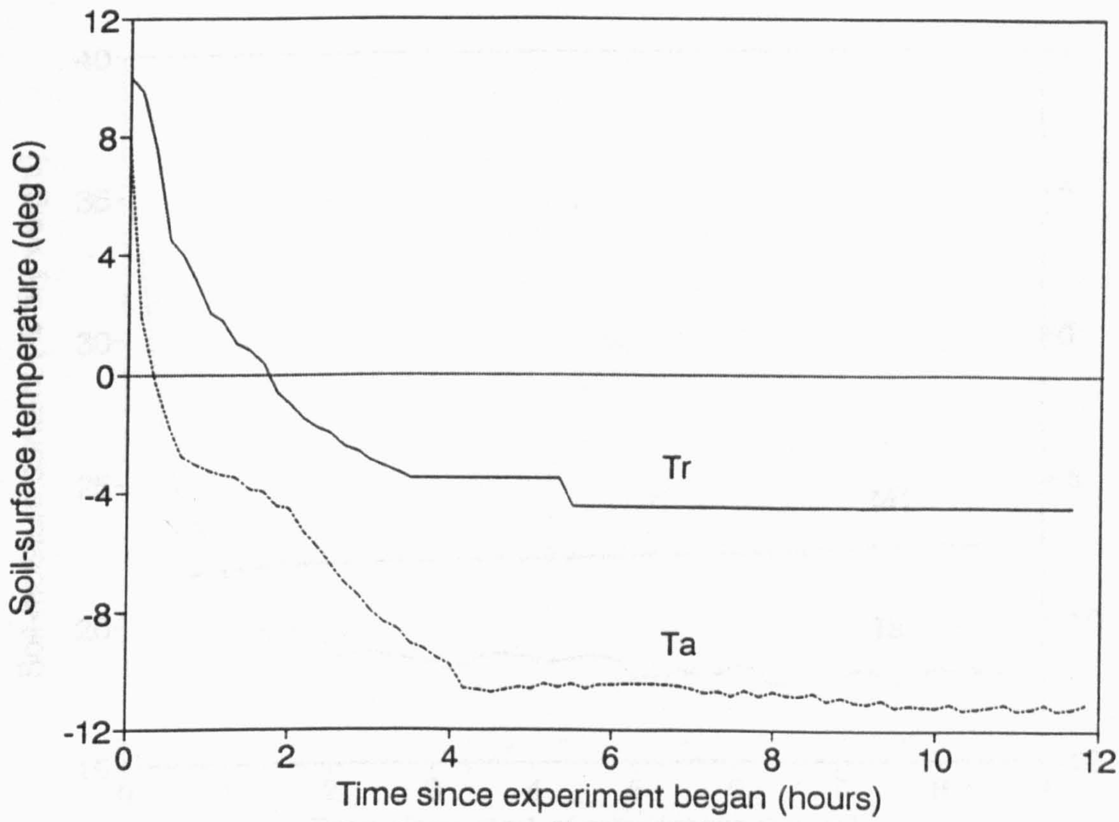

Figure 6.16 : Experiment 5/12/90; required (T_r) and actual (T_a) soil-surface temperature

USB$_1$

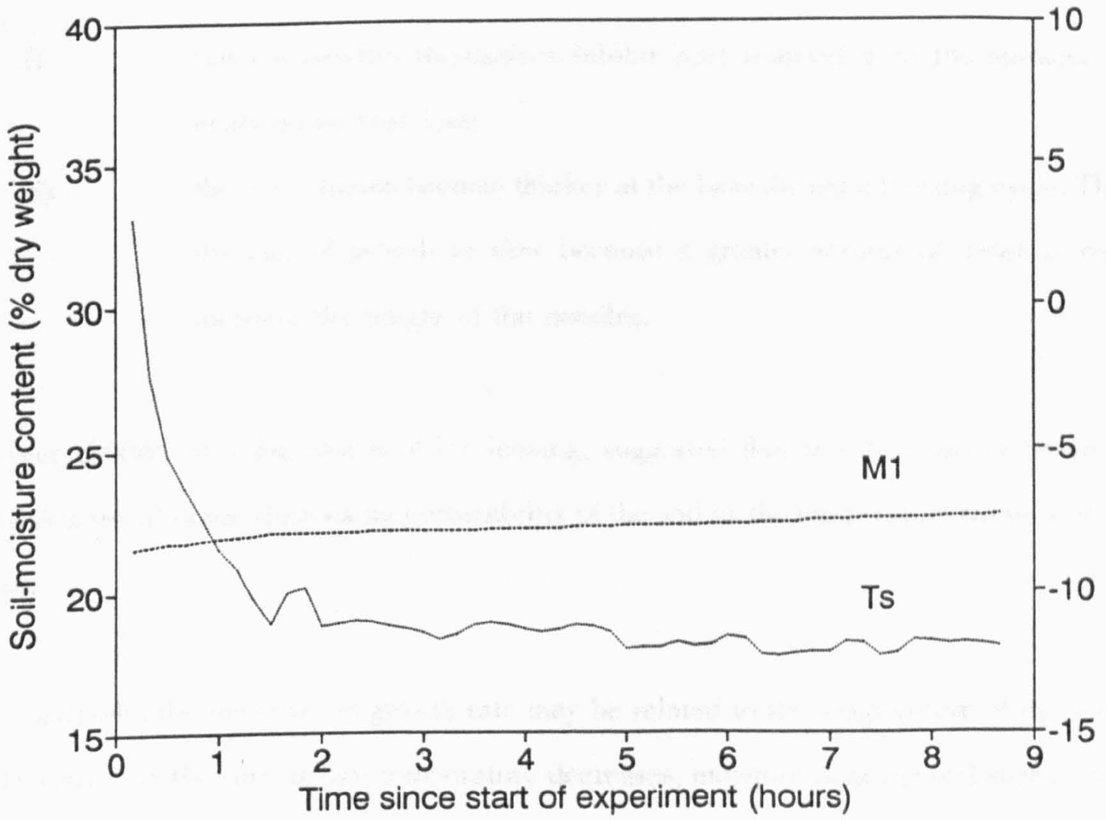

Figure 6.17 : Experiment 4/12/90; soil-moisture content and temperature

USB_1

There are few published figures of needle-ice growth rates because until recently measurement has been difficult (Section 5.2.5). Some relevant studies are summarised in Table 6.1. Soons and Greenland (1970) noted that the rate of crystal growth changed during the freezing cycle; crystals grew 8 mm h^{-1} in the initial stages of laboratory experiments and then 1 mm h^{-1} in later stages. Fukuda (1936) also determined that the rate of needle-ice growth was greatest immediately following nucleation and gradually decreased with time. The decrease in growth rate was thought to be caused by a combination of two factors (Fukuda, 1936):

i) the ice needles themselves inhibit heat removal from the surface, including evaporative heat loss;

ii) the ice columns become thicker at the base during a freezing cycle. This causes the rate of growth to slow because a greater volume of water is required to increase the length of the needles.

Penner (1986), in a discussion of ice lensing, suggested that the decrease in heave rate with time is a result of the decreasing permeability of the soil as the temperature drops at the freezing front.

Alternatively, the decrease in growth rate may be related to the temperature of the water in the soil profile. As the soil-surface temperature decreases, moisture near the soil surface cools until it is at the nucleation temperature. Ice then forms, at which point all the water below 0°C freezes immediately, and results in an initial high rate of crystal growth. The growth rate then reduces as water has to be 'pulled' from further down the soil profile and then cooled before it can be frozen.

Typical profiles of needle-ice growth from the present series of experiments are shown in Figures 6.18 and 6.19. These profiles indicate that the rate of growth is non-linear, and usually

Table 6.1 : Some example growth rates of needle-ice crystals

Author	Site	Growth rate ($mm\ h^{-1}$)
Fukuda (1936)	Agricultural plot, Japan	2.6 - 3.2
Hayward and Barton (1969)	Slope, New Zealand	18.0
Outcalt (1970)	Agricultural plot. Vancouver, B.C.	1.2
Soons and Greenland (1970)	Laboratory	1 - 8.0
Pickering (1988), Polkinghorne (1988)	Laboratory	0.3 - 1.3
Lawler (in press)	River bank. South Wales	0.17 - 1.71
Present study	Laboratory	0.1 - 7.0

decreases with time. (The actual rate of growth was controlled by the heat removal at the soil surface and the soil-moisture content (Section 6.3.3).) Two different patterns of growth were observed: smooth (Figure 6.18), and intermittent (Figure 6.19). Both types of profile produced needles that contained soil particles, and these are discussed in Chapter 7.

6.3.1 Smooth growth pattern

Figure 6.18 shows a typical smooth growth profile. Outcalt (1970a) presented a similar growth profile (Figure 6.20).

In the laboratory, clear needles (Section 3.2.1) with this type of profile were produced under 'ideal' growth conditions (e.g. Figures 6.1 and 6.2), with a relatively high soil-moisture content, slow rate of cooling and final soil-surface temperatures in the range -1°C to -4°C. It is assumed that the heat removed at the soil surface was matched by the heat that flowed to the freezing front within the soil moisture, and allowed continuous ice segregation. (Needles that contained sediment were also formed with a smooth growth profile and the formation of these is discussed in Section 7.3.2.).

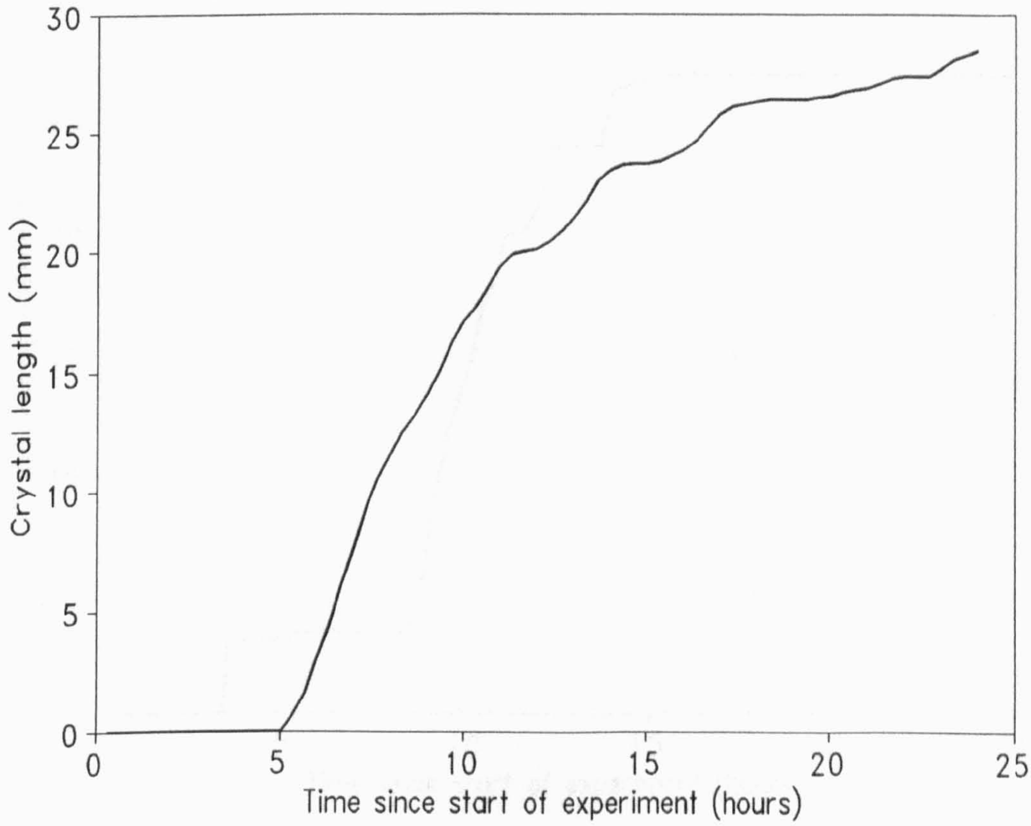

Figure 6.18 : Experiment 1/11/90; typical smooth growth profile DSE$_1$

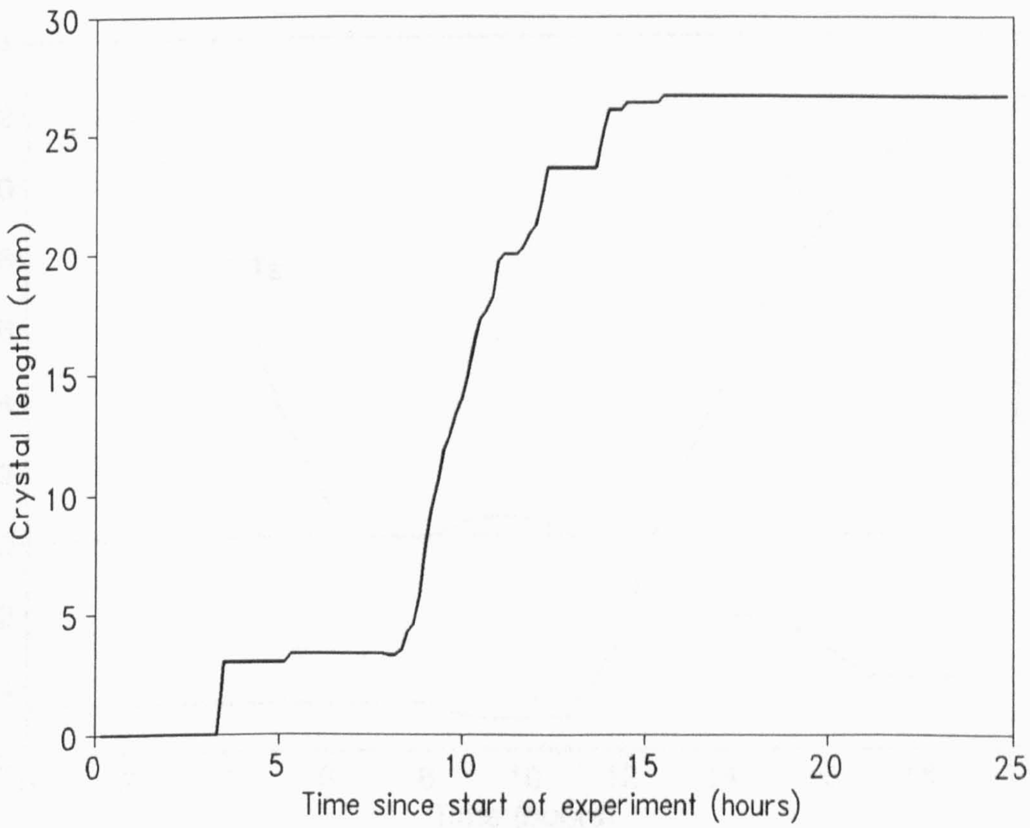

Figure 6.19 : Experiment 5/11/90; typical intermittent growth profile

DSE_1

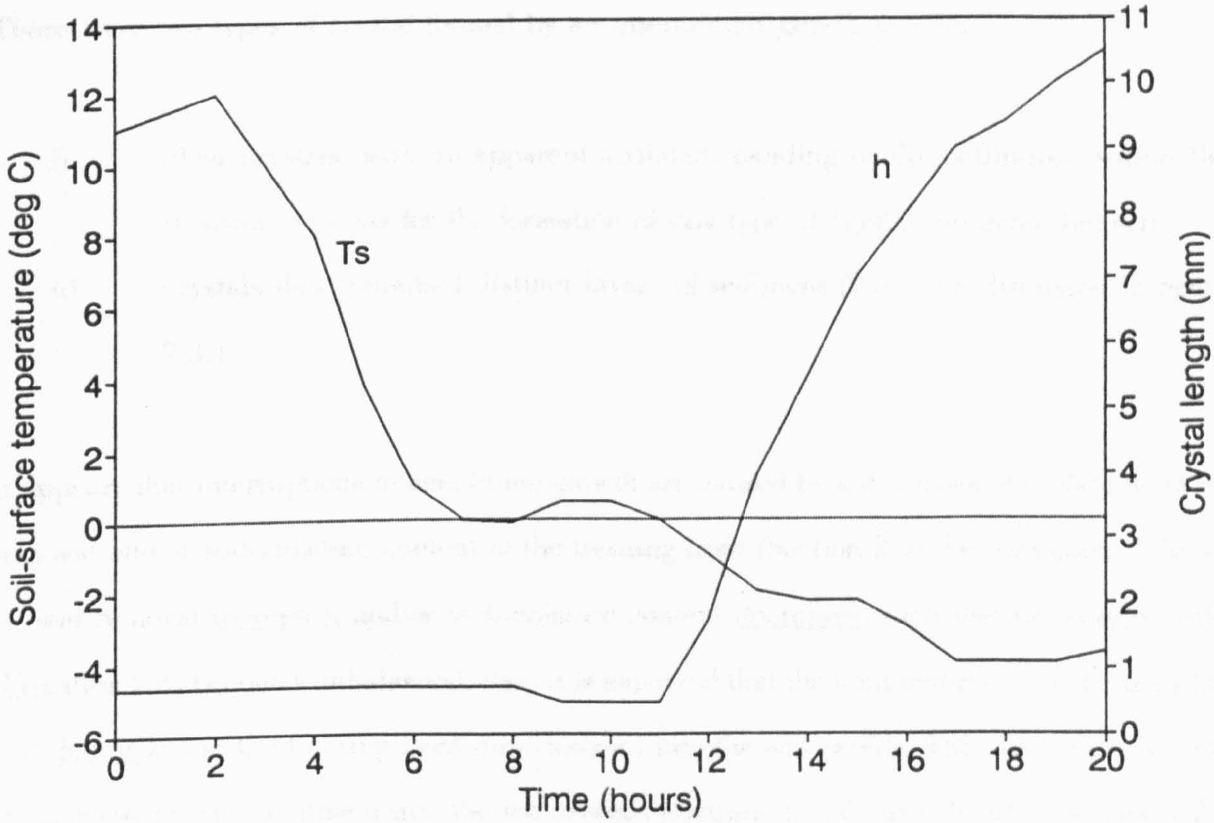

Figure 6.20 : Soil-surface temperature and needle-ice length, Vancouver (Outcalt, 1970a)

6.3.2 Intermittent growth pattern

An intermittent pattern of growth (Figure 6.19) was characterised by one or more breaks in needle-ice growth, which were usually followed by a rapid increase in the height of the crystal. As explained in Section 5.2.5 this does not reflect an inertia effect associated with the displacement transducers. It is thus concluded that breaks in growth are naturally occurring phenomena.

There were two types of crystal formed by an intermittent growth profile:

i) clear crystals, with no apparent sediment banding or discontinuities within them (possible reasons for the formation of this type of crystal are given below);

ii) crystals that contained distinct layers of sediment (these are discussed in Section 7.3.1).

It appears that interruptions to needle-ice growth are caused by a disturbance to the rate of heat removal and/or soil-moisture content at the freezing front (Section 2.5). For example, if the rate of heat removal <u>increases</u>, and/or soil-moisture content <u>decreases</u>, such that the energy budget (Equation 2.6) becomes unbalanced, then it is expected that the temperature at the freezing front will <u>decrease</u> and the freezing front may descend into the soil profile. This also seems to cause the incorporation of sediment into the ice crystals (discussed in further detail in Section 7.3.1).

During the formation of clear crystals, which showed an intermittent growth profile, however, no change in soil-surface temperature was observed (e.g. Figure 6.21). Thus, it appears that the disturbance to heat flow was caused by fluctuations in heat removal and/or soil-moisture content within the soil profile. Both the temperature and moisture content in the soil profile <u>increased</u>. It appears, therefore, that the interruptions to growth were caused by a <u>decrease</u> in the rate of heat removal from the freezing front. This is thought to result from the arrival of discrete parcels

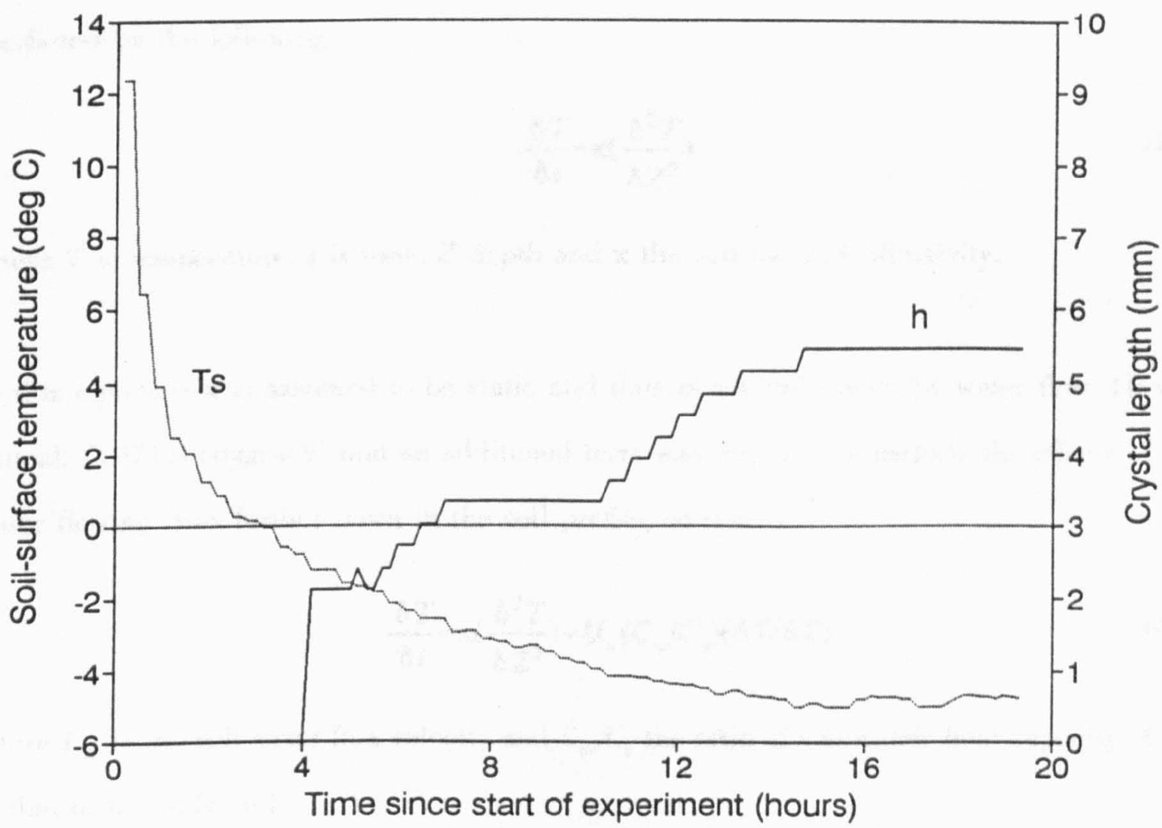

Figure 6.21 : Experiment 13/11/90; soil-surface temperature and crystal length USB$_1$

of relatively warm moisture at the freezing front and the reasons behind this suggestion are given below.

6.3.2a Pulses in soil-moisture flux. Outcalt (1971c) suggested that unsteady water flow can occur during needle-ice growth, and this may influence the flow of heat to the soil surface. He observed an irregularity (which he called a 'bump') in the parabolic Brunt cooling curve in the phases of cooling immediately prior to nucleation. This irregularity showed up as a large deviation from the predicted cooling rate at 5 cm depth in the soil when the cooling rate was predicted by the following

$$\frac{\delta T}{\delta t} - \kappa\left(\frac{\delta^2 T}{\delta Z^2}\right) \qquad (6.1)$$

where T is temperature, t is time, Z depth and κ the soil thermal diffusivity.

In this equation κ is assumed to be static and thus is not influenced by water flow. However, Outcalt (1971c) suggested that an additional term was required to include the effects of warm water flowing from further down in the soil profile, so that

$$\frac{\delta T}{\delta t} - \kappa\left(\frac{\delta^2 T}{\delta Z^2}\right) + U_w(C_w/C_s)(\delta T/\delta Z) \qquad (6.2)$$

where U_w is the soil water flux velocity and C_w/C_s the ratio of volumetric heat capacity of water to that of the bulk soil.

The expression $U_w(C_w/C_s)(\delta T/\delta Z)$ of Equation 6.2 describes the change in temperature caused by water flow to the soil surface. This term is thought to be important on two occasions during a freezing cycle (Outcalt, 1971c):

i) during the period of the moisture pulse when soil water is flowing upward along the temperature gradient towards the cooling surface;

ii) following nucleation when warm water is flowing towards the freezing front.

These pulses in water flux may occur during the late evening and early morning (Outcalt, 1971c).

It is postulated that such pulses of moisture may have caused needle-ice growth to cease in the present study. The flow of moisture to the freezing front is thought to have been of sufficient magnitude to cause the temperature at the freezing front to rise above 0°C. Thus needle-ice growth ceased, which shows up as a plateaux on the growth profile. When the temperature falls below 0°C, there is a sufficient supply of water at the freezing front to enable needle-ice growth to recommence at a rapid rate. (An example of this is given in the Section 6.3.2b.) Beskow (1935) also discussed the effect of warm water on needle-ice growth. He noticed that on a road cut in Stockholm warm water flowed out of the slope and prevented a continuous cover of needle ice developing.

6.3.2b An example of the effect of increased moisture on needle-ice growth. Results from a typical experiment where pulses of moisture seemed to affect needle-ice growth are displayed in Figure 6.22. (A similar pattern of moisture flow was observed in c.30% of experiments on both types of soil sample.) The soil-moisture content fluctuated markedly from hour 4 until the end of the experiment, and not just in the early stages of cooling and nucleation, as suggested by Outcalt (see above). This difference may be a result of the differences in the mechanism of cooling of the samples in nature and the laboratory. There were eight main peaks in moisture content which are labelled A-H (Figure 6.22).

It appears that the upper limit of soil-moisture content in this particular experiment was c.57%. When this value was reached, needle-ice growth at the soil surface ceased. There was a time lag of 10 to 20 minutes before the effects of the increase in moisture were noticed at the soil

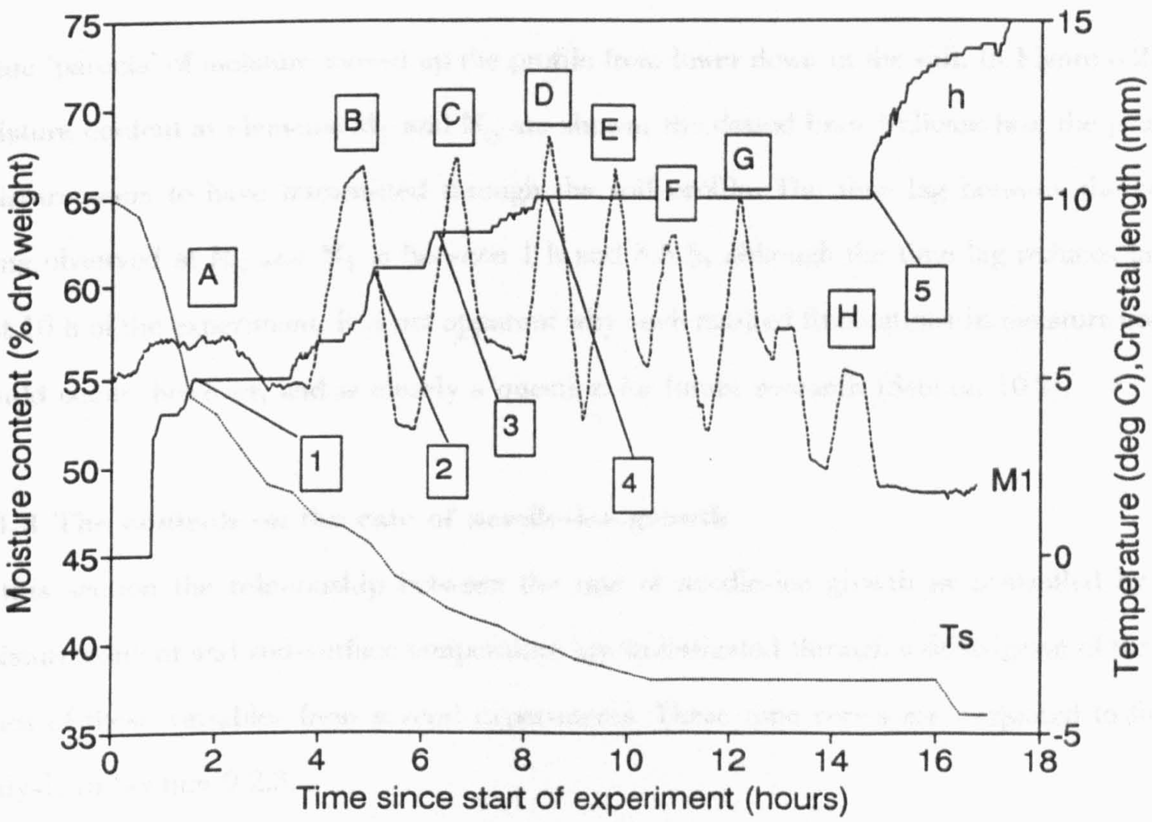

Figure 6.22 : Experiment 10/7/91; an example where pulses of soil-moisture content were observed USB_1

surface. For example, the increase of moisture leading up to peak A probably caused needle-ice growth to cease at point 1. The increase in moisture to peaks B, C and D also caused needle-ice growth to cease at points 2, 3 and 4 respectively. After peak D needle-ice growth was not observed for six hours, even though the moisture content fell below the 57% threshold. This is probably because the moisture content fell for an insufficient time to allow adequate cooling to occur to allow ice segregation to continue. After peak G the moisture content fell and remained below the 57% threshold and thus ice segregation became continuous (from point 5).

These 'parcels' of moisture moved up the profile from lower down in the soil. In Figure 6.23 the moisture content at elements M_1 and M_5 are shown; the dotted lines indicate how the peaks of moisture seem to have transmitted through the soil profile. The time lag between the pulses being observed at M_5 and M_1 is between 1 h and 3.5 h, although the time lag reduces in the first 10 h of the experiment. It is not apparent why such marked fluctuations in moisture content should occur, however, and is clearly a question for future research (Section 10.2).

6.3.3 The controls on the rate of needle-ice growth

In this section the relationship between the rate of needle-ice growth as controlled by soil-moisture content and soil-surface temperature are investigated through a description of the time series of these variables from several experiments. These time series are subjected to further analysis in Section 9.2.3.

Nakaya and Magono (1944) suggested that there was a relationship between the rate of needle-ice growth and water flow. They stated that the amount of frost heaving was proportional to the excessive water drawn from the soil beneath the freezing front. A similar association between the rates of moisture flow and needle-ice growth has been detected in the present study.

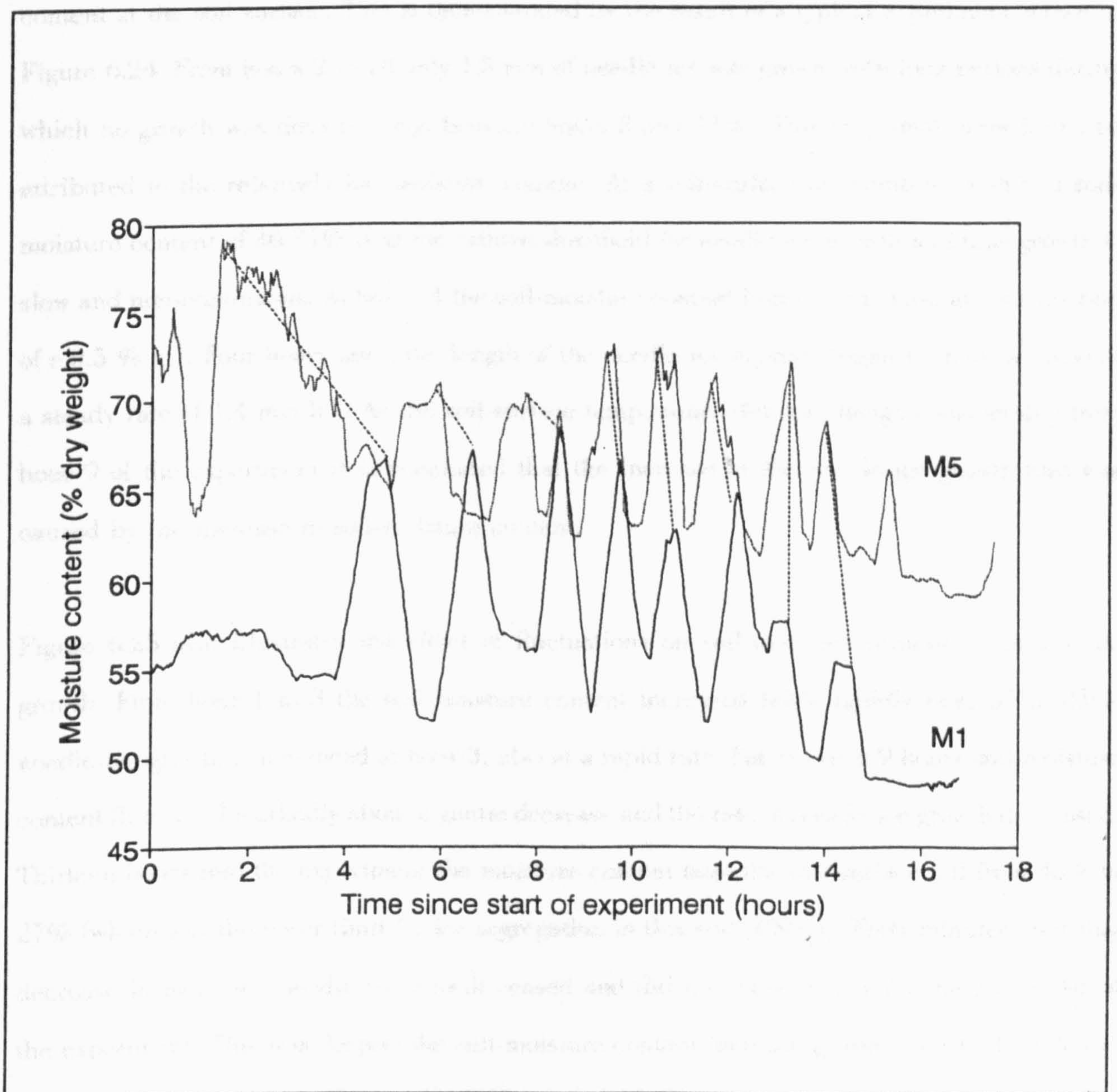

Figure 6.23 : Experiment 10/7/91; moisture content at M_1 and M_5 **USB_1**

In this chapter it has been suggested that the timing of ice nucleation, ice segregation and the total length of ice crystals is dependent on the moisture content at, and just below, the soil surface, and the relationship between moisture and soil-surface temperature. It is expected, therefore, that the rate of needle-ice growth will be closely related to changes in the moisture content at the soil surface. This is demonstrated by the result of a typical experiment shown in Figure 6.24. From hours 2 to 18 only 1.5 mm of needle ice was grown, with long periods during which no growth was detected (e.g. between hours 8 and 11.5). This very small growth can be attributed to the relatively low moisture content. At a soil-surface temperature of -4°C a soil-moisture content of 30-31% is at the critical threshold for needle-ice growth and thus growth is slow and non-continuous. At hour 14 the soil-moisture content began to increase at a steady rate of c.0.5 % h^{-1}. Four hours later, the length of the needle-ice crystals began to increase, also at a steady rate of 1.4 mm h^{-1}. As the soil-surface temperature did not change considerably from hour 9 of the experiment it is concluded that the increase in the needle-ice growth rate was caused by the increase in soil-moisture content.

Figure 6.25 also illustrates the effect of fluctuations on soil-moisture content on needle-ice growth. From hour 1 to 3 the soil-moisture content increased fairly rapidly from 37 to 43%, needle-ice growth commenced at hour 3, also at a rapid rate. For the next 9 hours soil-moisture content fluctuated markedly about a gentle decrease and the rate of needle-ice growth decreased. Thirteen hours into the experiment the moisture content near the soil surface fell from 43% to 27% (which was the lower limit for ice segregation in this soil (USB_1)). Forty minutes after this decrease in moisture, needle-ice growth ceased and did not recommence for the remainder of the experiment. This was despite the soil-moisture content increasing from 26% to 41% in the last 7 h of the experiment. The needle-ice crystals had a layer of in-situ frozen soil at their base. It is suggested that ice segregation did not recur following the increase in moisture because of the low temperature at the soil surface (-8°C). There was probably more heat being removed from

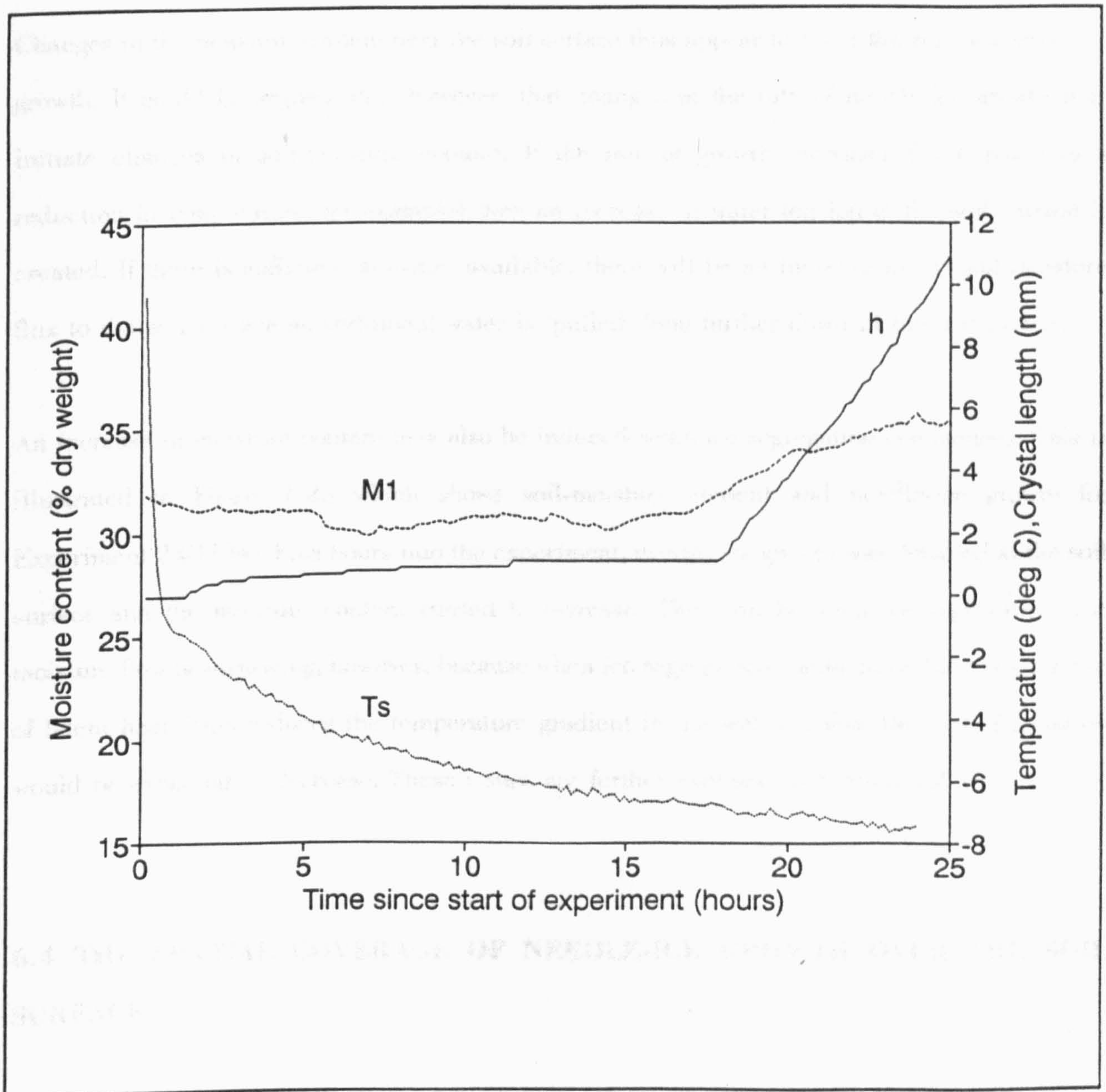

Figure 6.24 : Experiment 14/3/91; soil-surface temperature, moisture content near the soil surface and crystal length USB$_1$

the soil surface than was supplied by the soil moisture (thus creating an imbalance in the energy budget). It is not apparent why soil-moisture content should have decreased so rapidly, although it may reflect the trough between the passage of two pulses of moisture.

Changes in the moisture content near the soil surface thus appear to affect the rate of needle-ice growth. It could be argued also, however, that changes in the rate of needle-ice growth may initiate changes in soil-moisture content. If the rate of growth increases (as a result of a reduction in temperature, for example) then an increase in water tension at the soil surface is created. If there is sufficient moisture available, there will be an increase in the soil-moisture flux to the soil surface as additional water is 'pulled' from further down in the soil profile.

An increase in moisture content may also be induced when ice segregation commences. This is illustrated in Figure 6.26 which shows soil-moisture content and needle-ice growth for Experiment 23/11/90. Five hours into the experiment, needle-ice growth was detected at the soil surface and the moisture content started to increase. This link between ice segregation and moisture flow is surprising, however, because when ice segregation commences there is a release of latent heat. This reduces the temperature gradient in the soil and thus the flux of moisture would be expected to decrease. These issues are further explored in Section 9.2.4.

6.4 THE SPATIAL COVERAGE OF NEEDLE-ICE GROWTH OVER THE SOIL SURFACE

In this section the spatial distribution of needle-ice cover over the soil surface is described, with particular reference to the difference in cover between samples DSB_1 (disturbed) and USB_1 (undisturbed). (Figure 6.27 shows the locations from which the needle-ice and soil samples, discussed in this section, were taken.) Figures 6.28 and 6.29 show maps of the typical

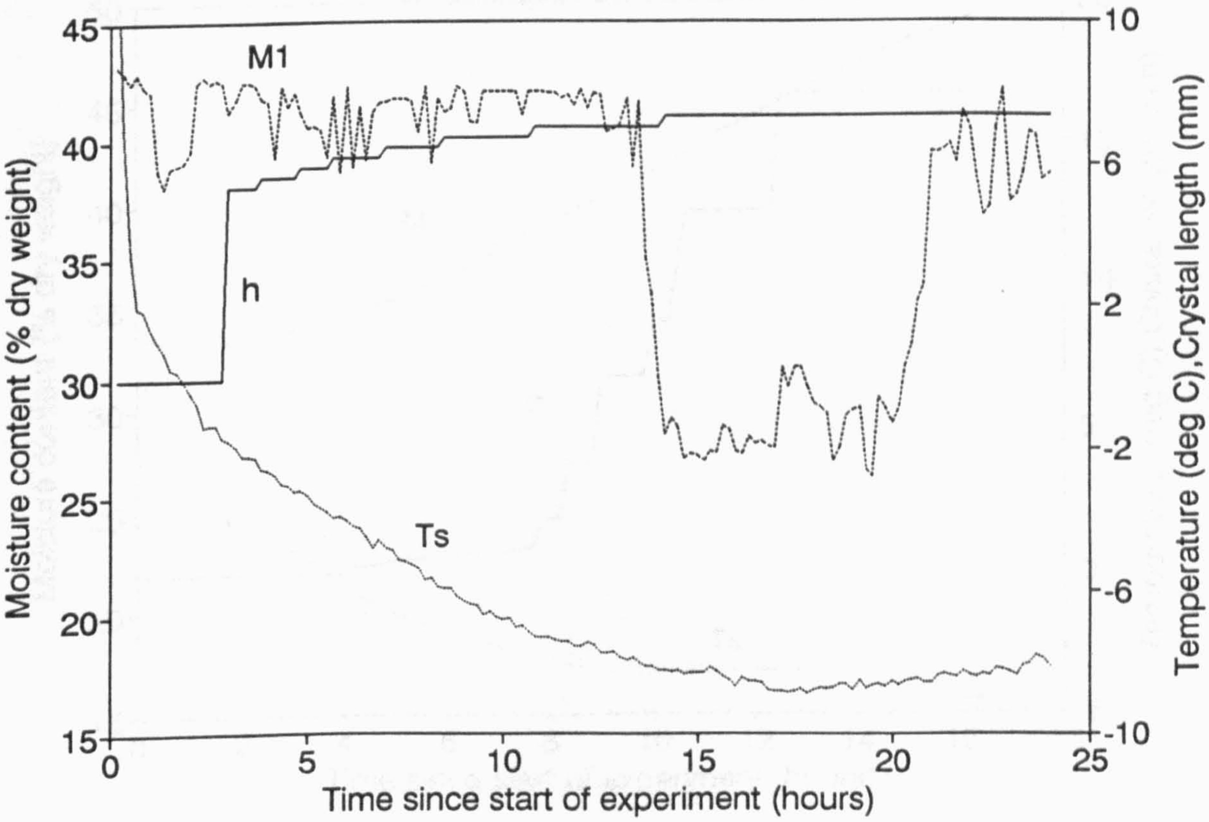

Figure 6.25 : Experiment 11/2/91; soil-surface temperature, soil-moisture content and crystal length USB$_1$

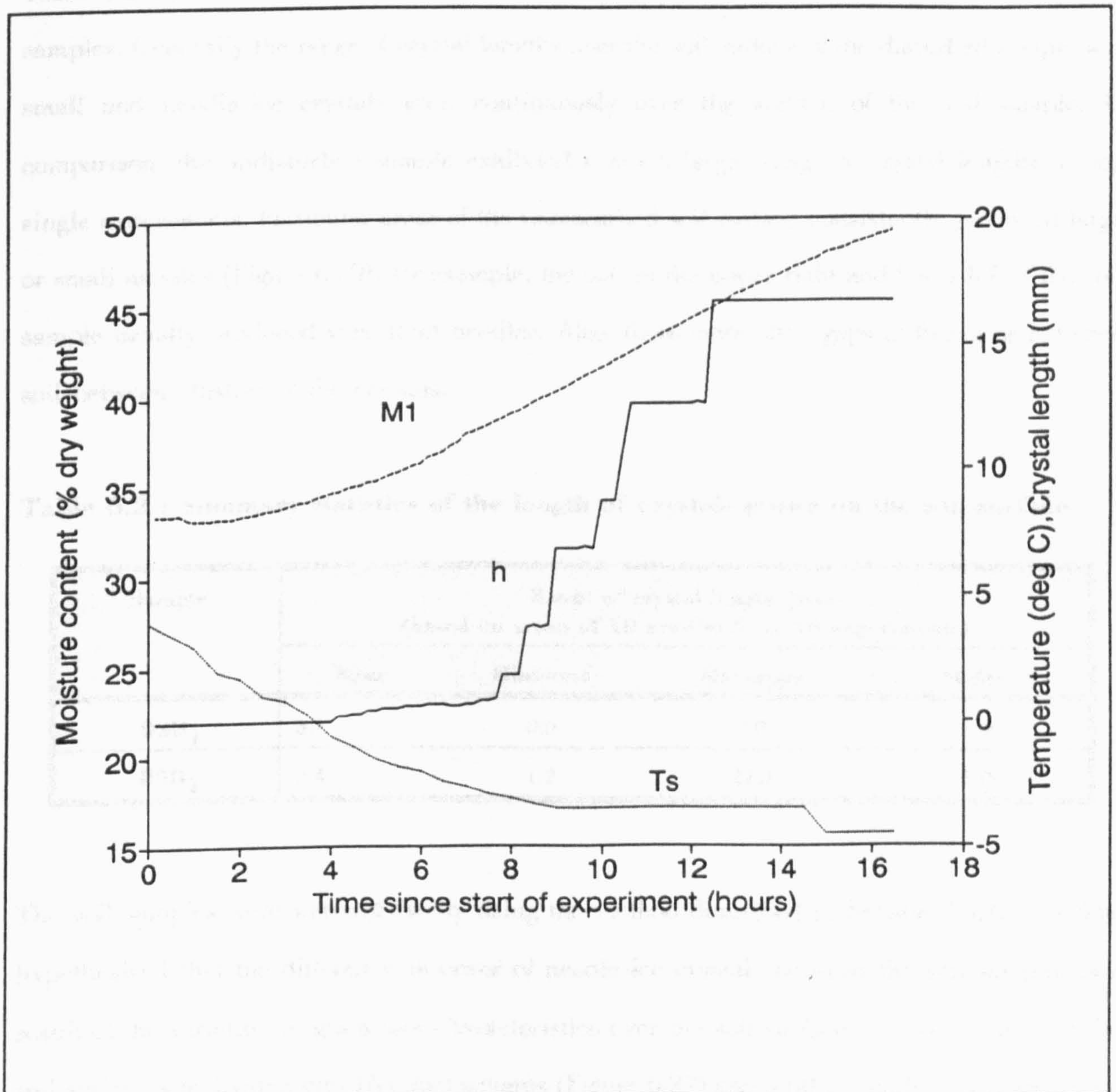

Figure 6.26 : Experiment 23/11/90; moisture content surface and crystal length USB$_1$

distribution of needle-ice lengths on each soil surface (based on the mean of 10 crystals randomly selected from each square).

Table 6.2 shows the summary statistics of the range of crystals lengths on both of the soil samples. Generally the range of crystal lengths over the soil surface of the disturbed sample was small and needle-ice crystals grew continuously over the surface of the soil sample. In comparison, the undisturbed sample exhibited a much larger range of crystal lengths during single experiments. Particular areas of the undisturbed soil surface consistently produced large or small needles (Figure 6.29); for example, the soil in the upper right and lower left of the soil sample usually produced very short needles. Also, there were often gaps of frozen or unfrozen soil between clusters of the crystals.

Table 6.2 : Summary statistics of the length of crystals grown on the soil surface

Sample	Range of crystal length (mm) (based on mean of 10 needles from 30 experiments)			
	Mean	Minimum	Maximum	St.dev.
DSB_1	3.1	0.0	7.0	1.9
USB_1	6.4	1.2	22.3	5.0

The soil samples were watered evenly using the method described in Section 5.3.1. It is thus hypothesised that the difference in cover of needle-ice crystals between the soil samples is a result of the variation in grain-size characteristics over the soil surface. To investigate this the soil surface was divided into 16 equal squares (Figure 6.27) and a 60 g sample of soil was taken from each square for grain-size analysis. (This analysis was undertaken at the end of the series of experiments.)

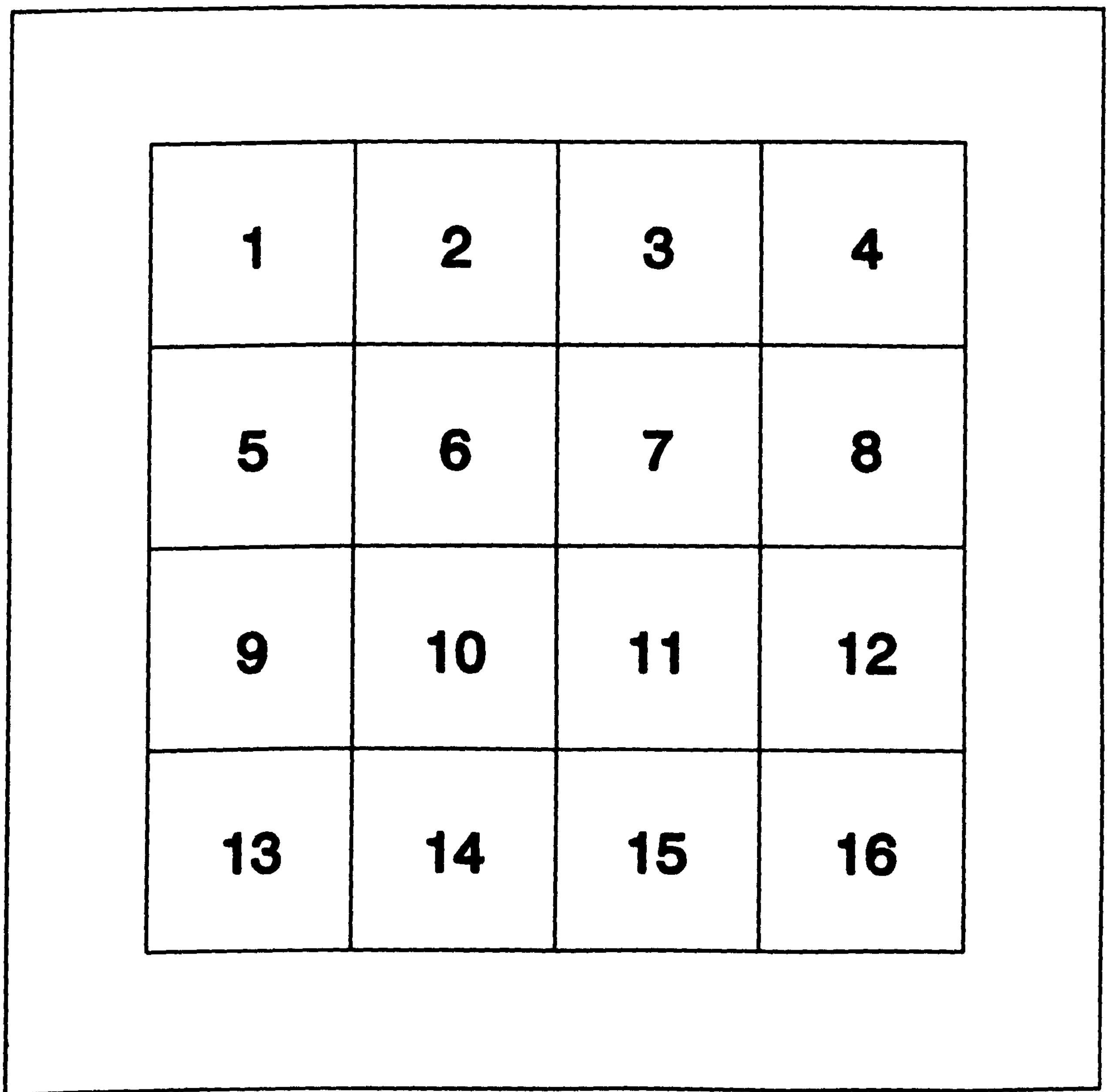

Figure 6.27 : Location from which the soil samples were taken from the soil surface (the numbers refer to the sampling grid)

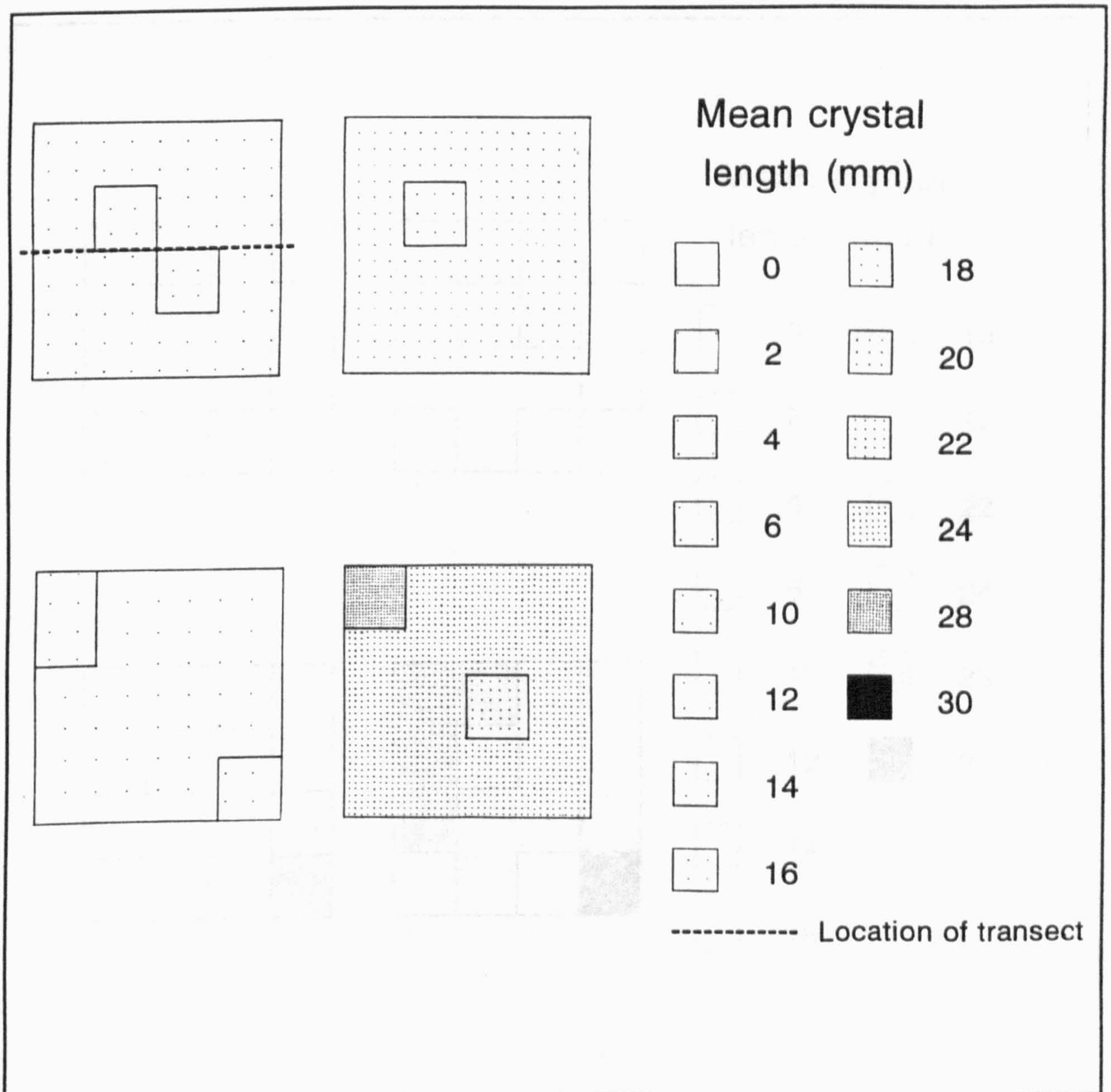

Figure 6.28 : Spatial distribution of needle-ice lengths over the surface of sample DSB_1 for four experiments

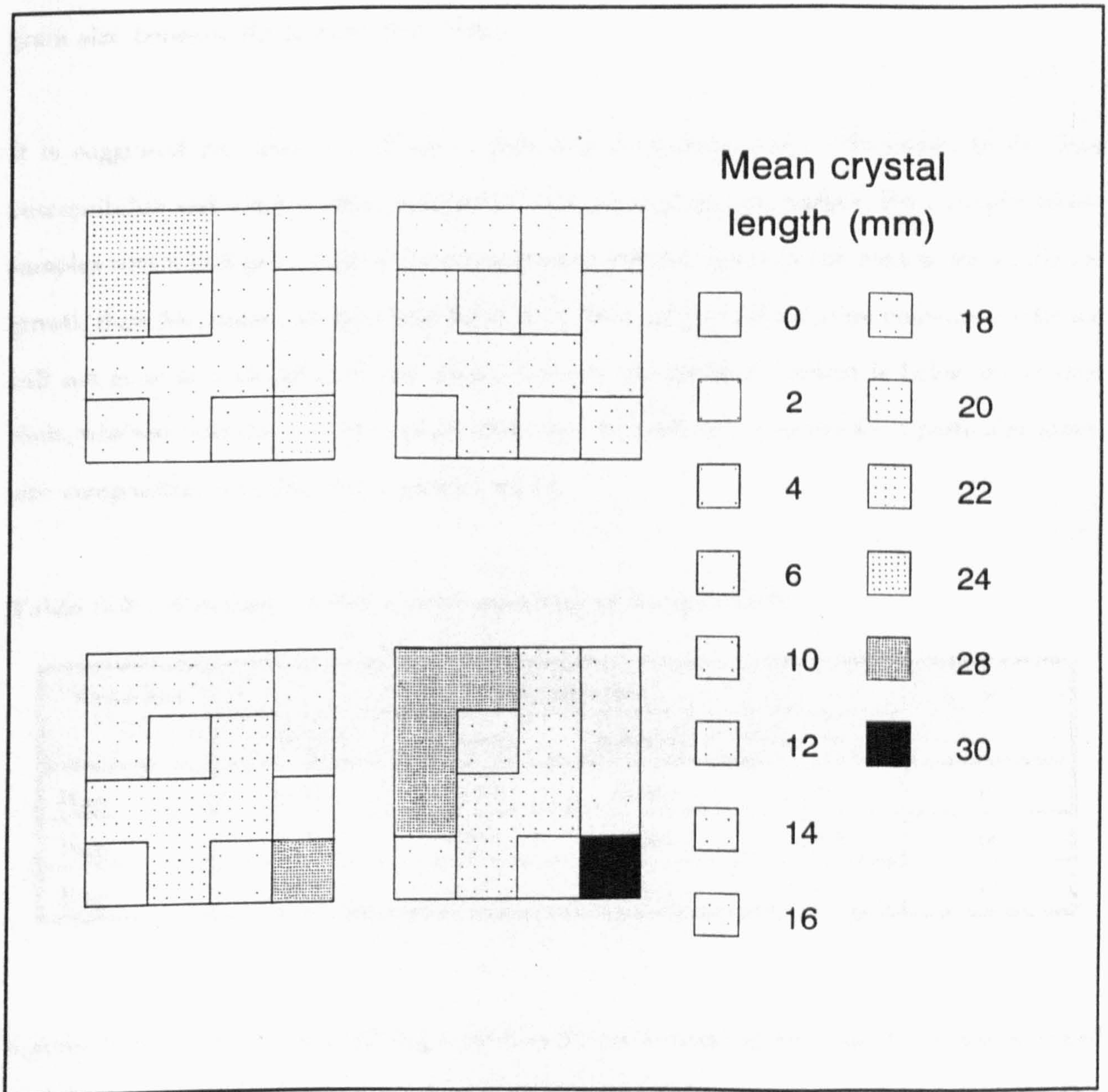

Figure 6.29 : Spatial distribution of needle-ice lengths over the surface of USB_1 for four experiments

Figures 6.30, 6.31, 6.32 and 6.33 show the grain-size distribution of the soil from sample DSB_1(summarised in Table 6.3) and Figures 6.34, 6.35, 6.36 and 6.37 the distribution of samples from USB_1 (summarised in Table 6.4). Whilst with sample DSB_1 the grain-size compositions over the soil surface were similar there were significant spatial differences in the grain size between the samples from USB_1.

It is suggested that these variations in grain-size composition cause differences in the frost susceptibility and water-holding capacity between areas of the soil surface. For example, those samples with a high percentage of fines may require a higher soil-moisture content for needle-ice growth than the coarser samples (see Table 2.3). Thus, at low soil-moisture contents needle ice will not grow in some areas of the sample because the moisture content is below the critical limit, whereas elsewhere on the sample there may be sufficient moisture for a particular grain-size composition, and needle-ice growth occurs.

Table 6.3 : Summary of the spatial sampling of sample DSB_1

Grain size	Grain size (mm)				n
	Mean	Minimum	Maximum	St.dev.	
D_{25}	0.019	0.009	0.023	0.003	16
D_{50}	0.056	0.035	0.090	0.013	16
D_{75}	0.189	0.175	0.225	0.015	16

Figures 6.38 and 6.39 show the D_{50} grain size for each sampling location. If Figures 6.29 and 6.39 are compared it can be seen that smaller crystals consistently grow on areas where the D_{50} is low (i.e. where the soil is finer) (e.g. in squares U12 and U13).

Crystal lengths were also measured in a transect across the middle of the soil samples (see Figure 6.28). This investigation was to determine whether the lengths of crystals were controlled

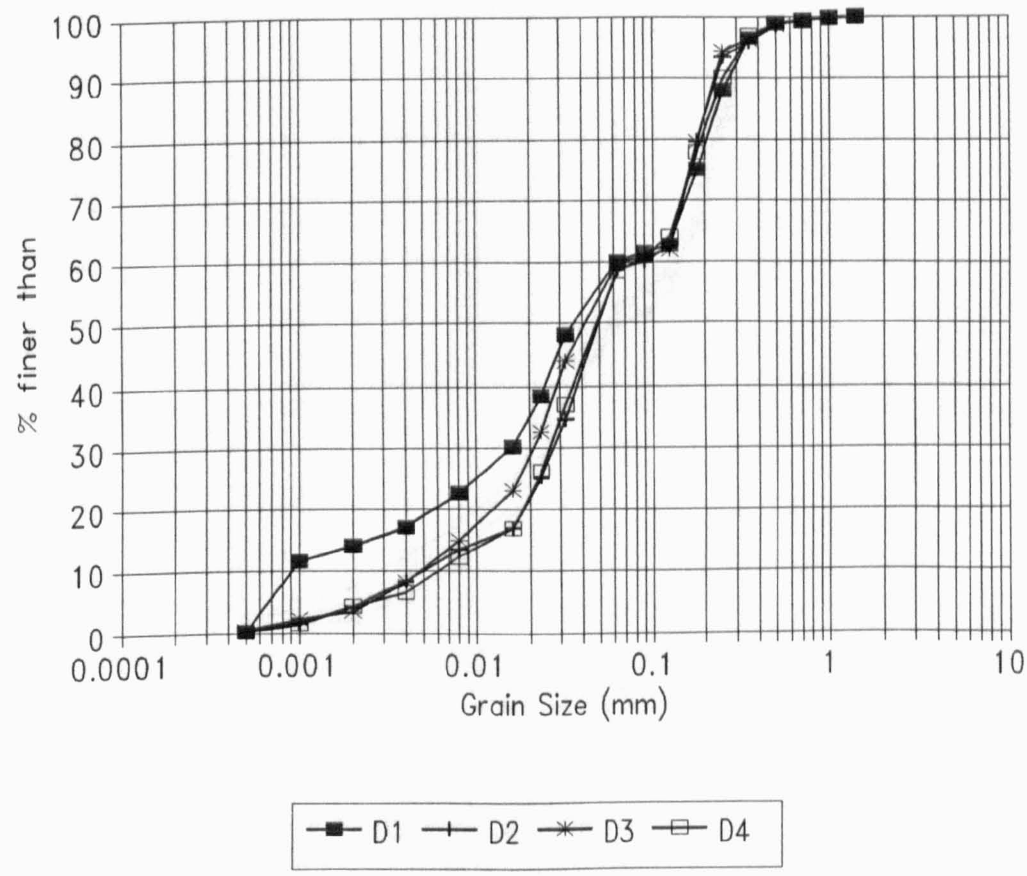

Figure 6.30 : Grain-size distribution of samples D1 - D4

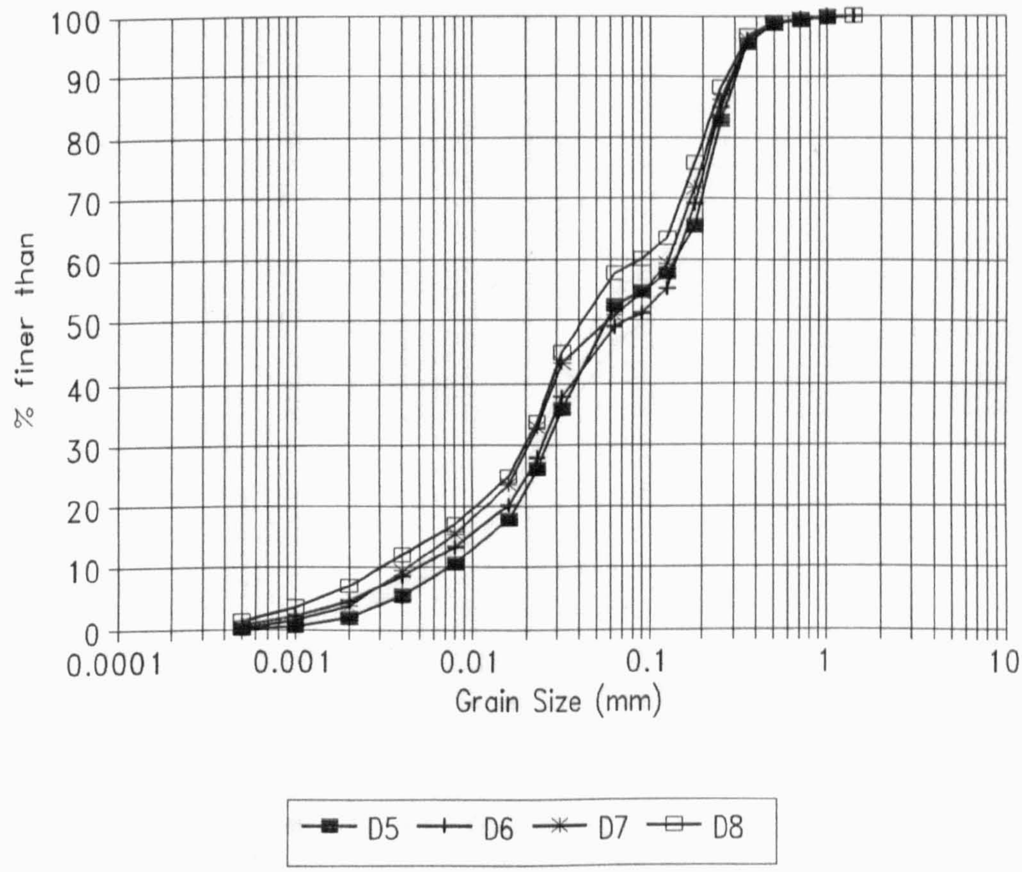

Figure 6.31 : Grain-size distribution of samples D5 - D8

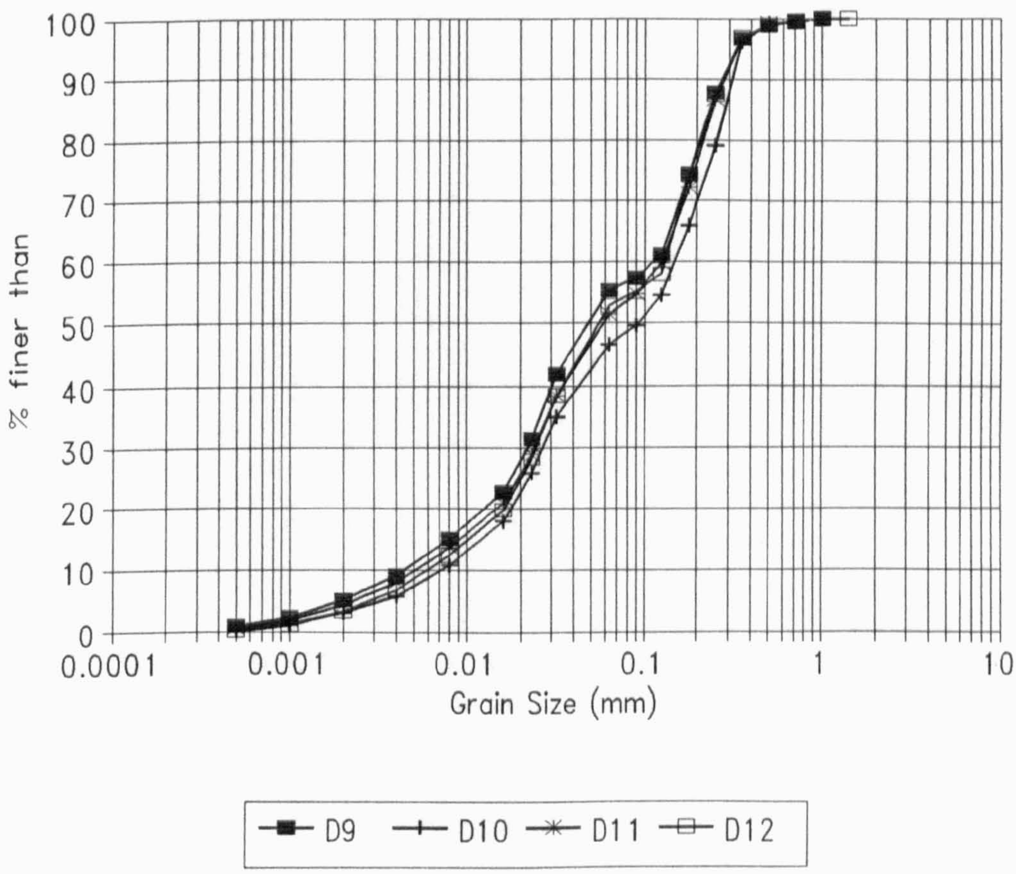

Figure 6.32 : Grain-size distribution of samples D9 - D12

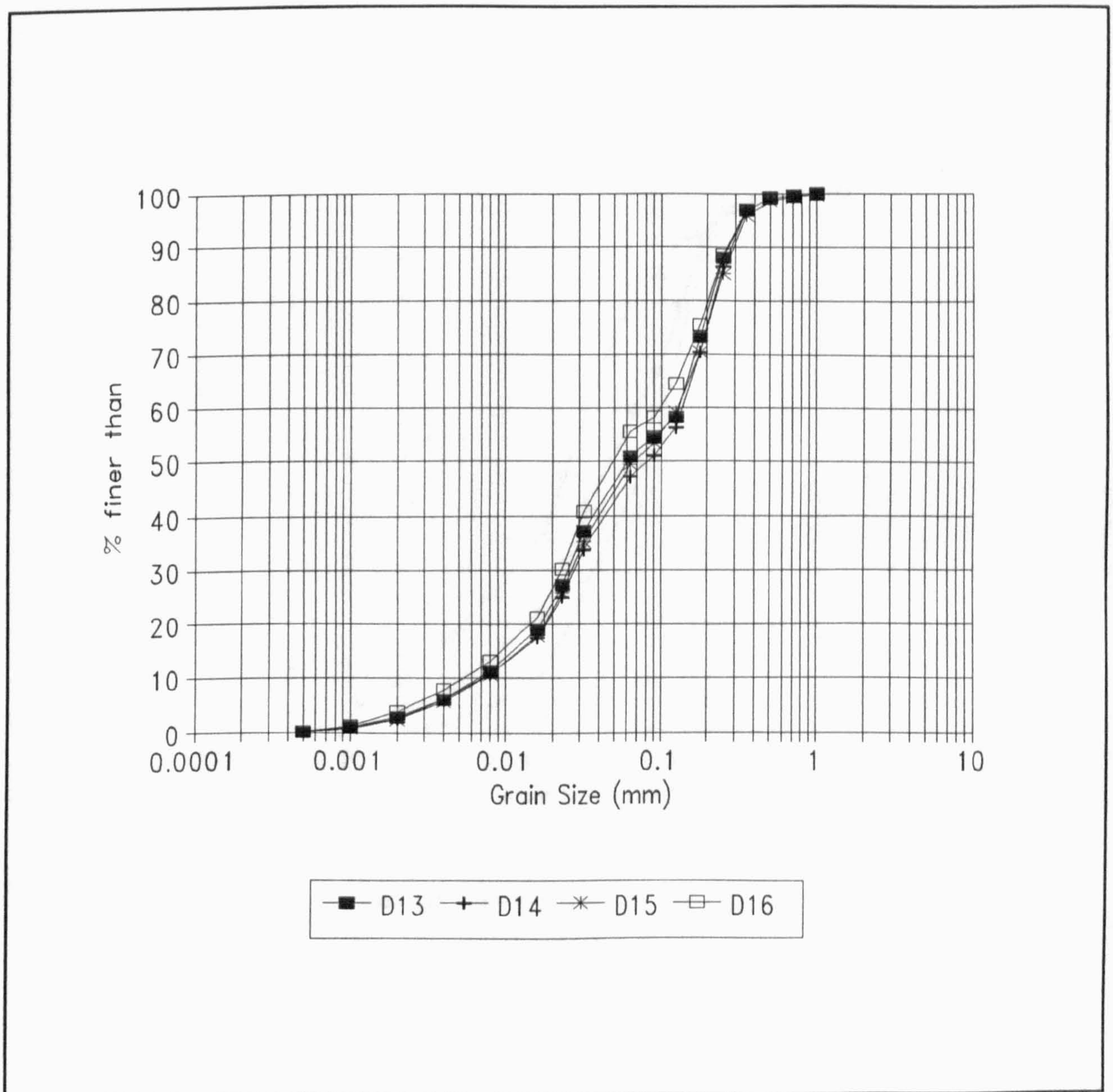

Figure 6.33 : Grain-size distribution of samples D13 - D16

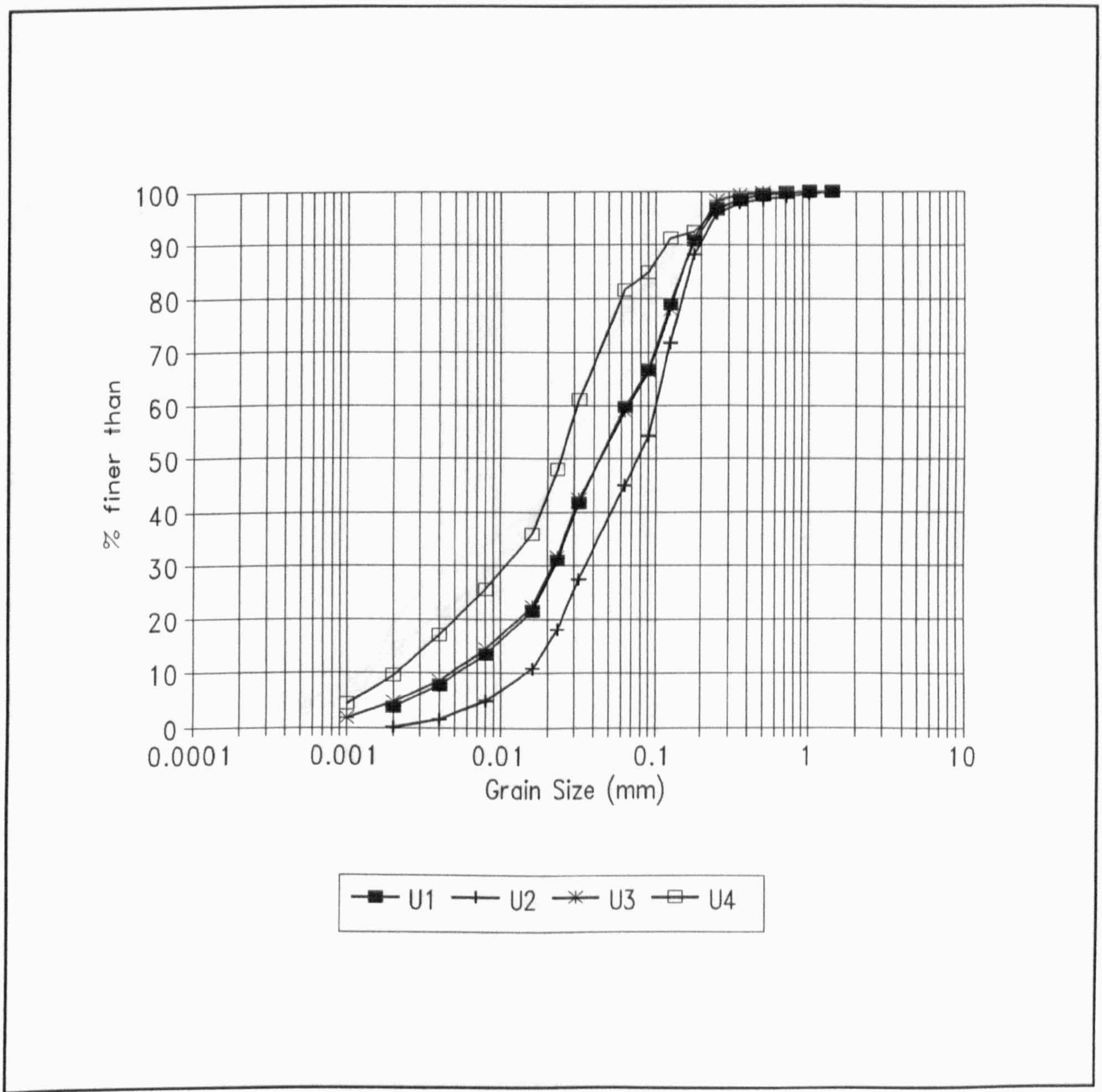

Figure 6.34 : Grain-size distribution of samples U1 - U4

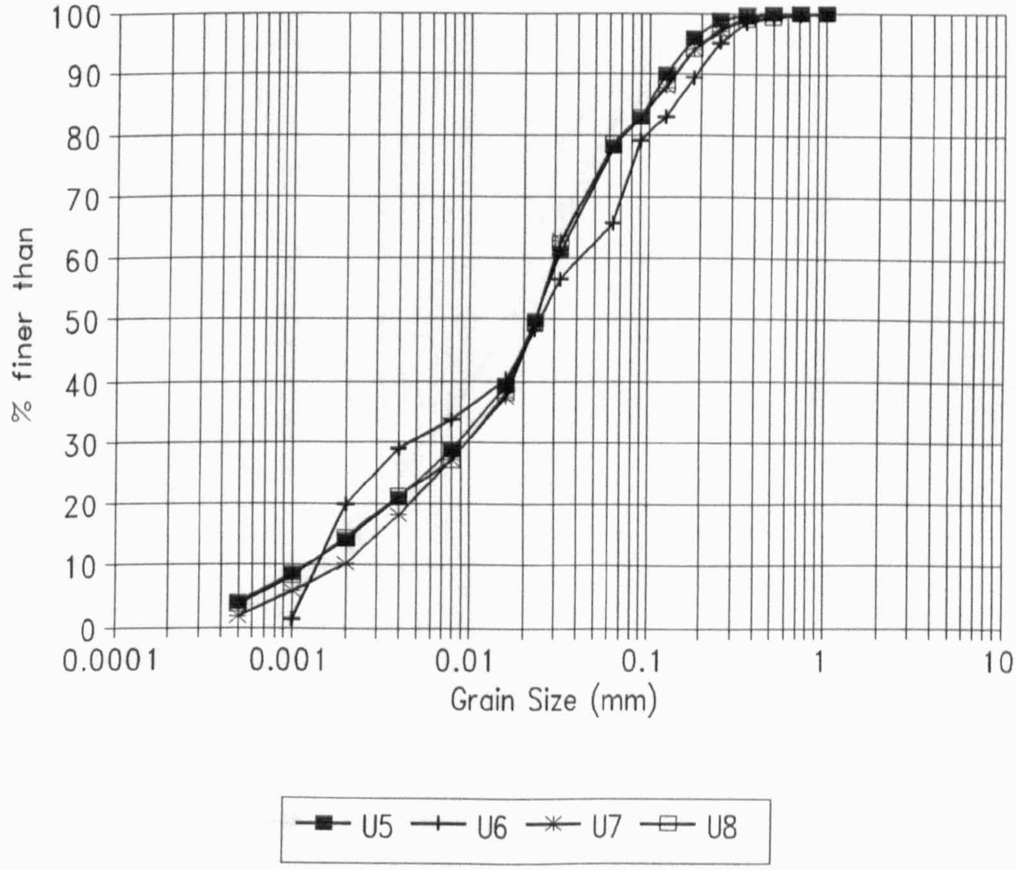

Figure 6.35 : Grain-size distribution of samples U5 - U8

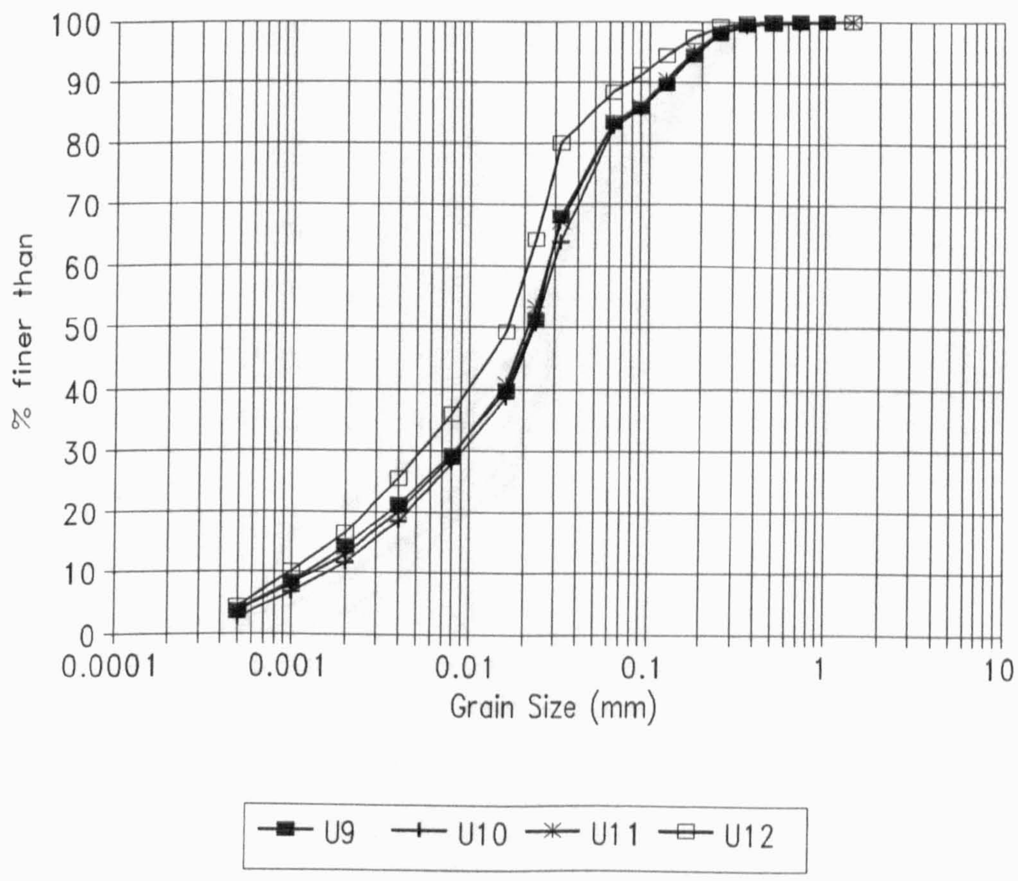

Figure 6.36 : Grain-size distribution of samples U9 - U12

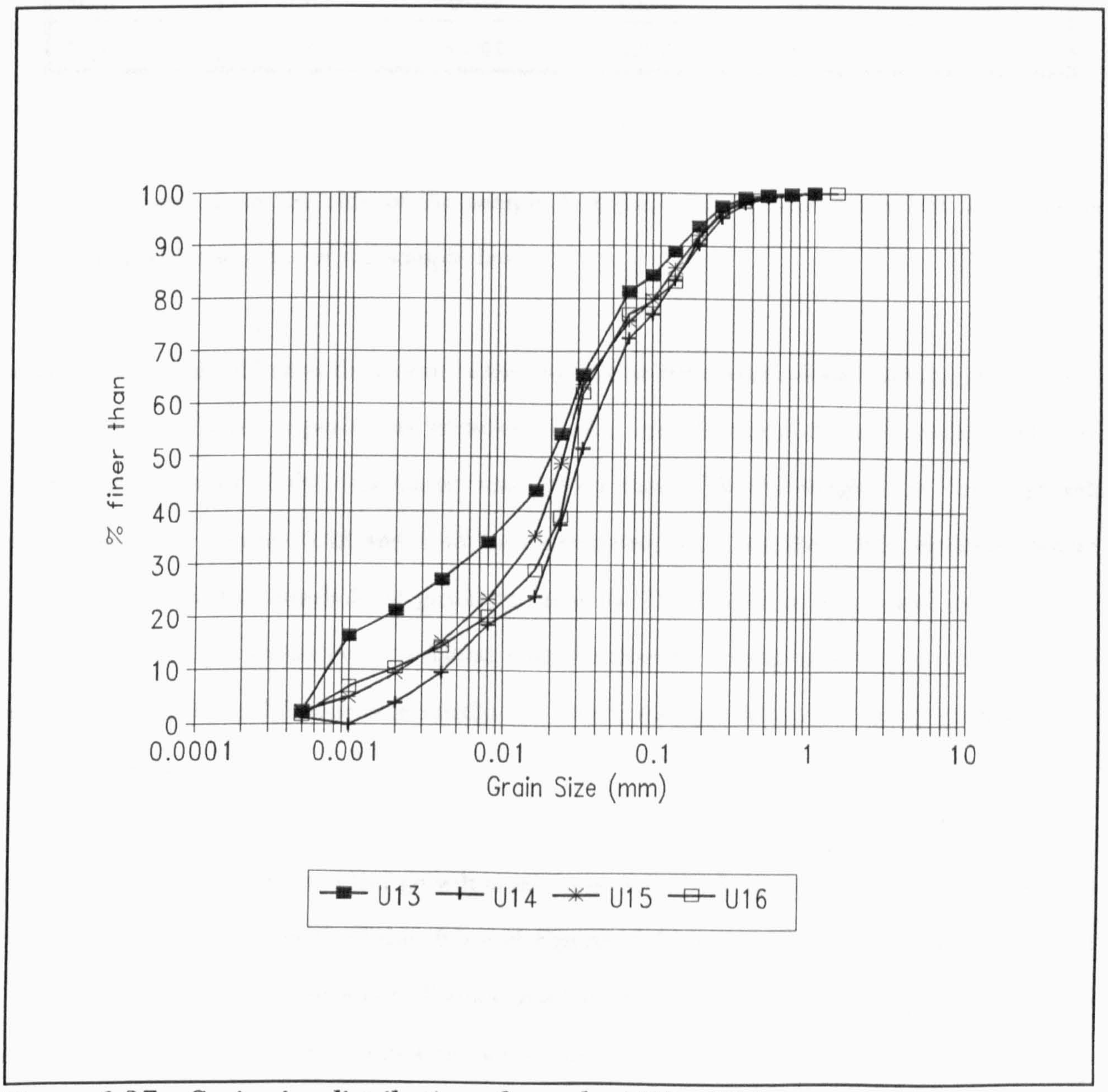

Figure 6.37 : Grain-size distribution of samples U13 - U16

Table 6.4 : Summary of the spatial analysis of sample USB_1

Grain size	Grain size (mm)				n
	Mean	Minimum	Maximum	St.dev.	
D_{25}	0.027	. 0.003	0.030	0.071	16
D_{50}	0.029	0.018	0.075	0.014	16
D_{75}	0.061	0.022	0.013	0.039	16

by the distance from the side of the sample box (i.e. whether there were any edge effects associated with the sides of the sample box).

Figures 6.40 and 6.41 show the results of the analysis on the disturbed and undisturbed samples respectively for three experiments (denoted in the legend) where the soil surface moisture content at the start of the experiment was greater than 35% dry weight (i.e. 'ideal' growth conditions) and Figures 6.42 and 6.43 for experiments with less than 30% moisture (where conditions are at the threshold of growth/no growth). The line of mean crystal length on the undisturbed sample shows more variation than the disturbed sample, and thus reinforces the suggestion about the differences in needle-ice cover over the soil surface being greater on the undisturbed sample.

In the experiments with the ideal growth conditions distance from the side of the box does not seem to affect crystal length (Table 6.5 and Figures 6.44 and 6.45). In the moisture limited experiments, however, there was a distinct trend in the crystal length (Table 6.5 and Figures 6.46 and 6.47). The crystals within 4 cm of the side of the sample were shorter than the crystals which grew in the centre of the sample. This is thought to occur because soil near to the edge of the box has a smaller potential catchment volume from which to draw moisture (shown schematically in Figure 6.48).

0.044	0.077	0.044	0.024
0.023	0.025	0.023	0.023
0.023	0.023	0.022	0.016
0.020	0.031	0.024	0.027

Figure 6.38 : DSB$_1$; D_{50} at each sampling location

0.035	0.050	0.041	0.049
0.060	0.060	0.075	0.041
0.050	0.094	0.057	0.055
0.060	0.081	0.068	0.050

Figure 6.39 : USB_1; D_{50} at each sampling location

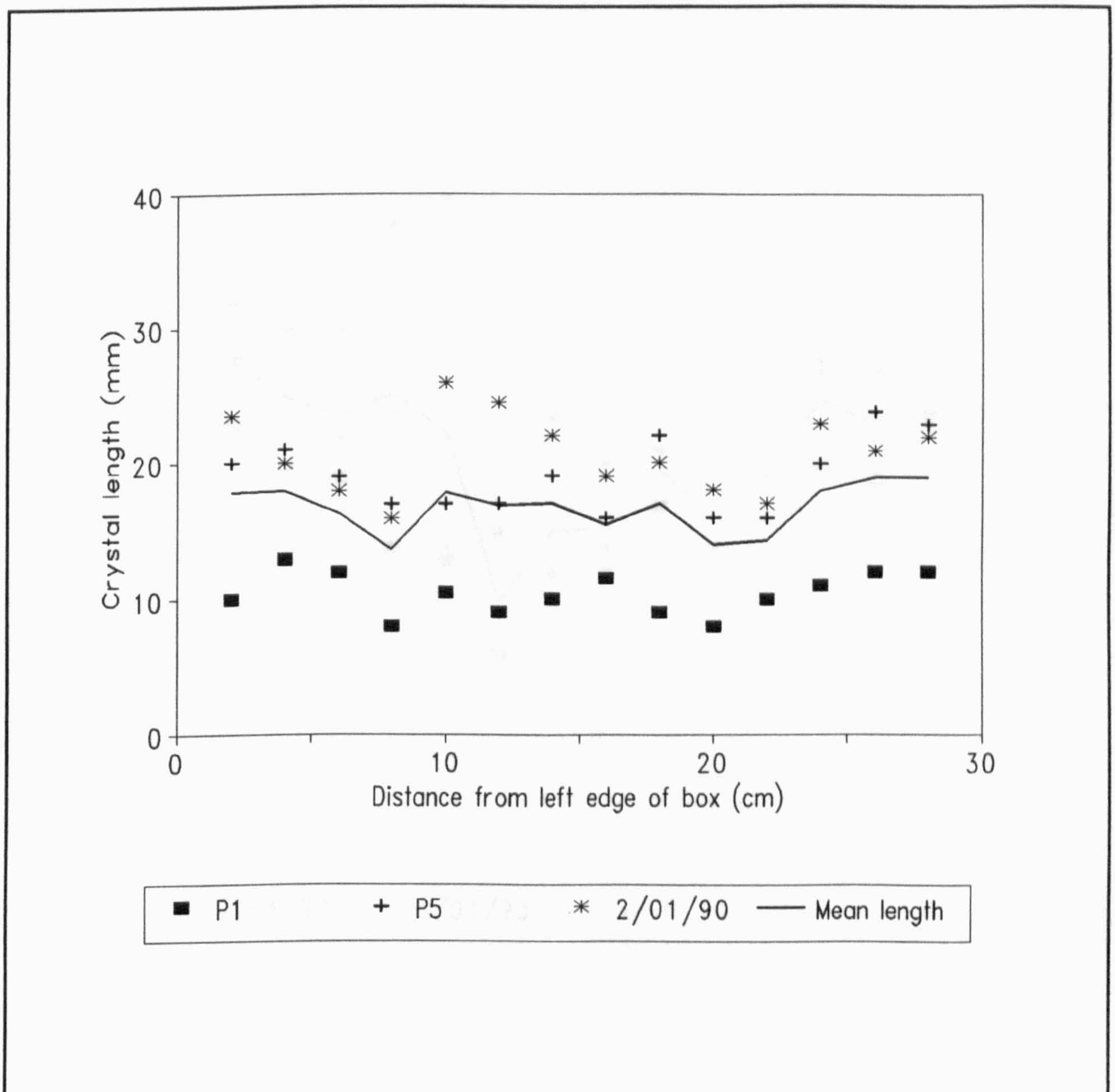

Figure 6.40 : DSB$_1$; transect of crystal length across the soil surface - saturated conditions

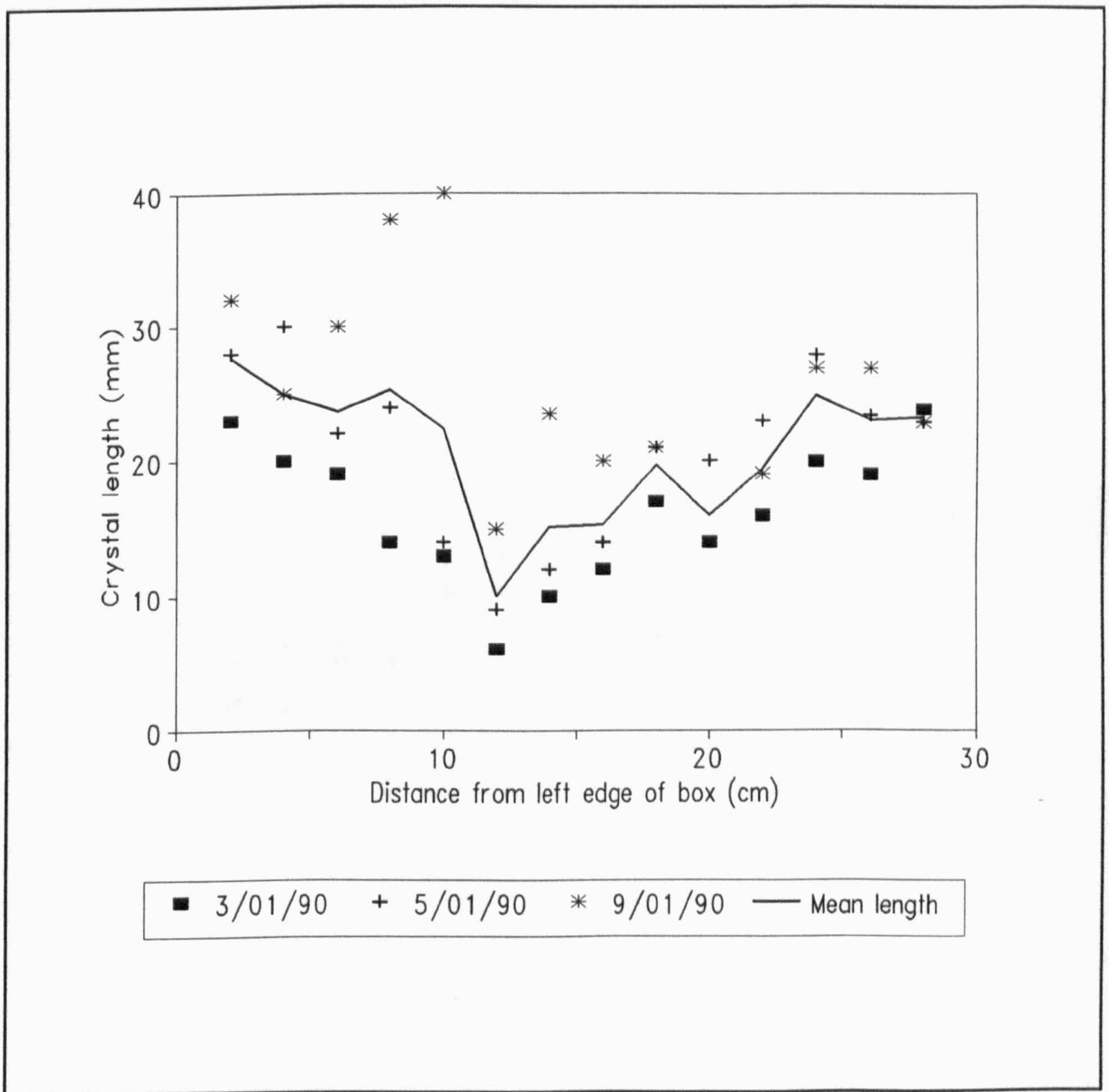

Figure 6.41 : USB_1; transect of crystal length across the soil surface - saturated conditions

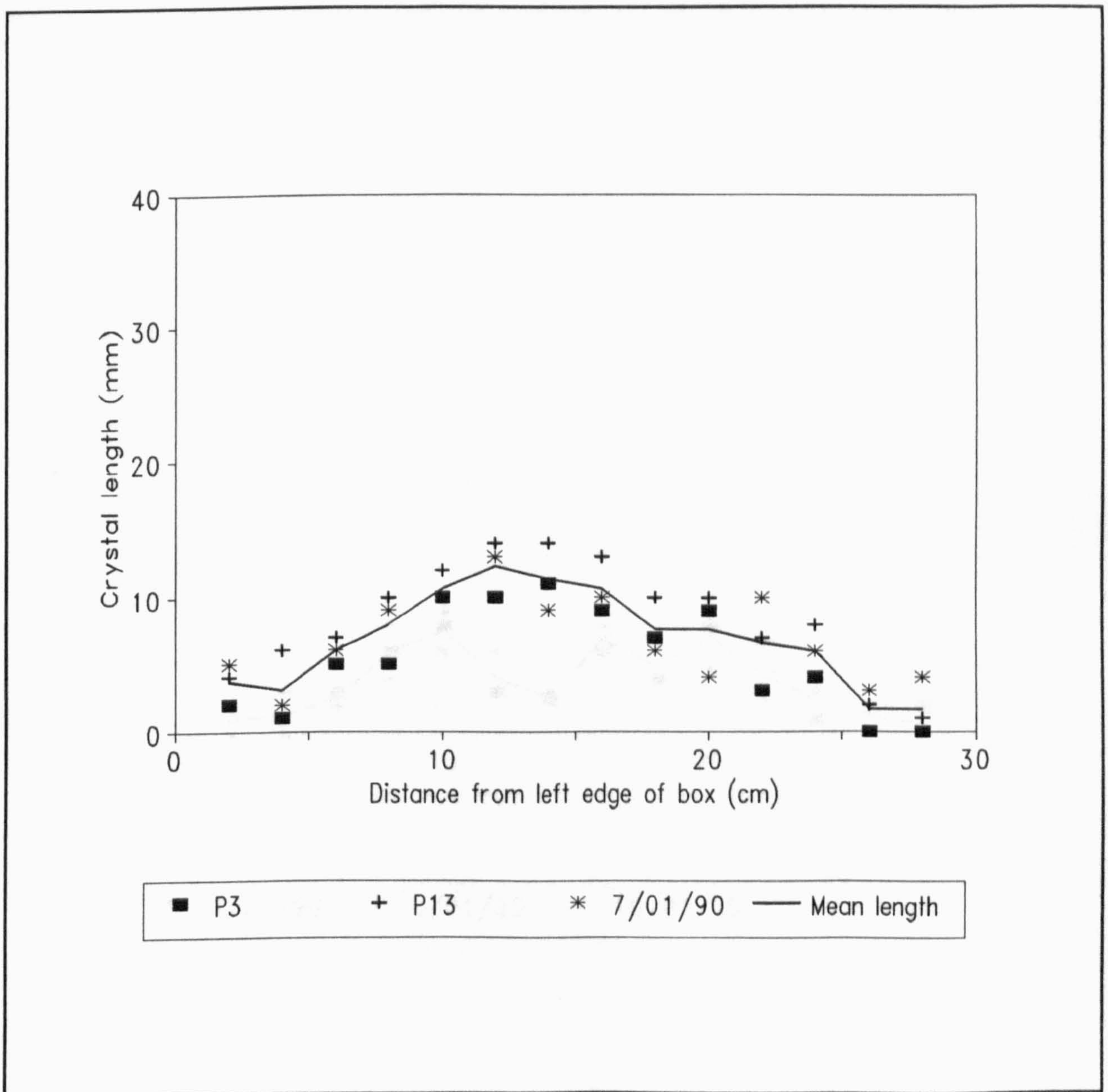

Figure 6.42 : DSB$_1$; transect of crystal length across the soil surface -conditions where moisture content was limited

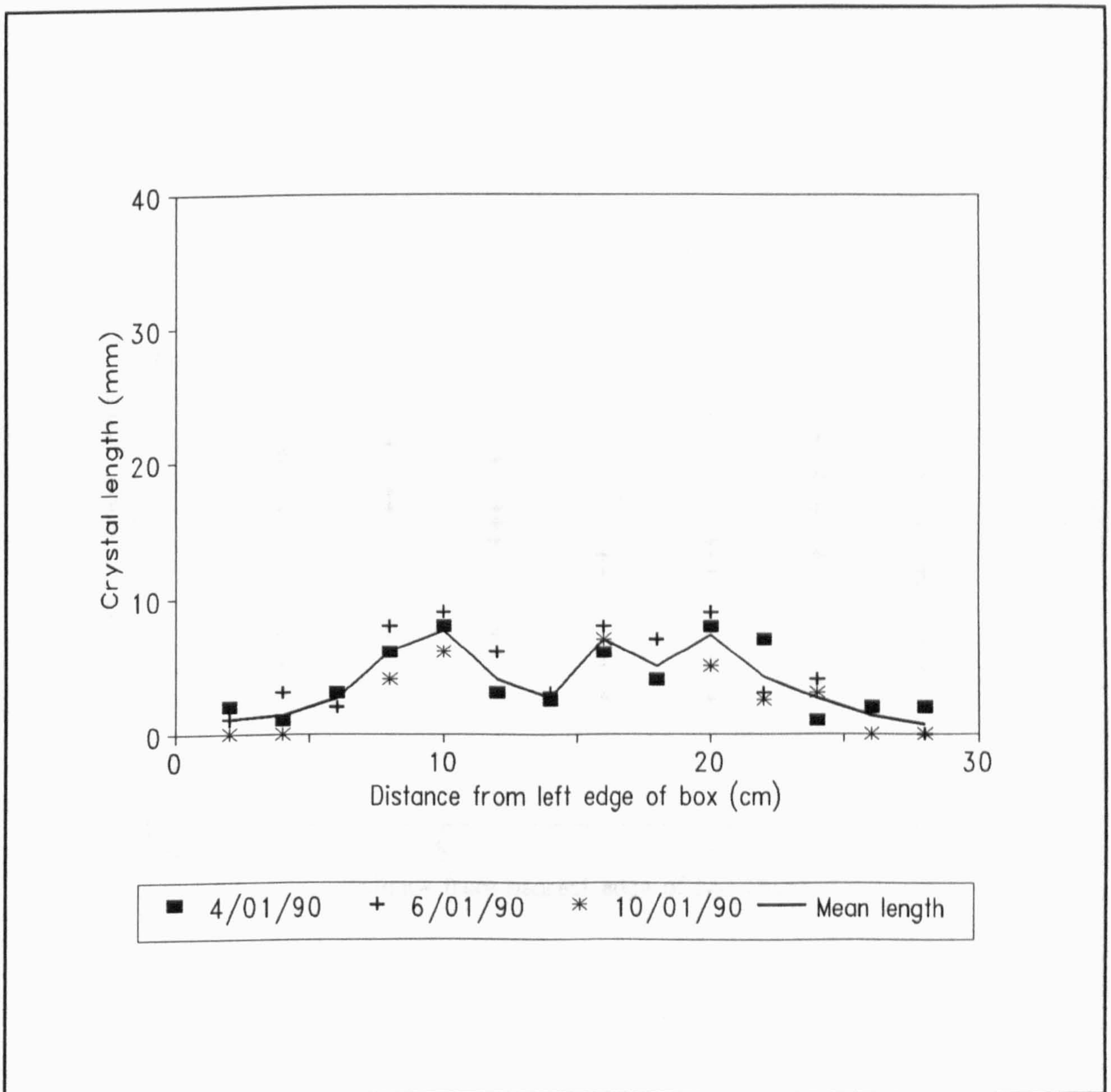

Figure 6.43 : USB_1; transect of crystal length across the soil surface -conditions where moisture content was limited

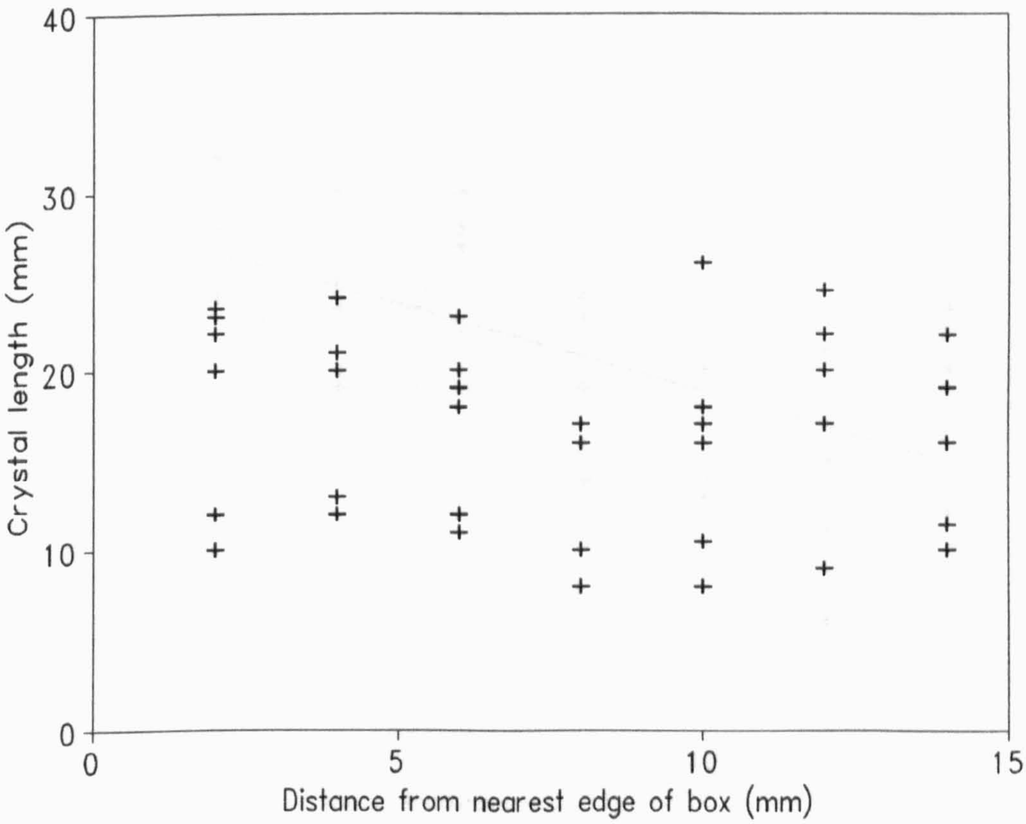

Figure 6.44 : DSB_1; the relationship between distance from the nearest edge of the box and crystal length - saturated conditions

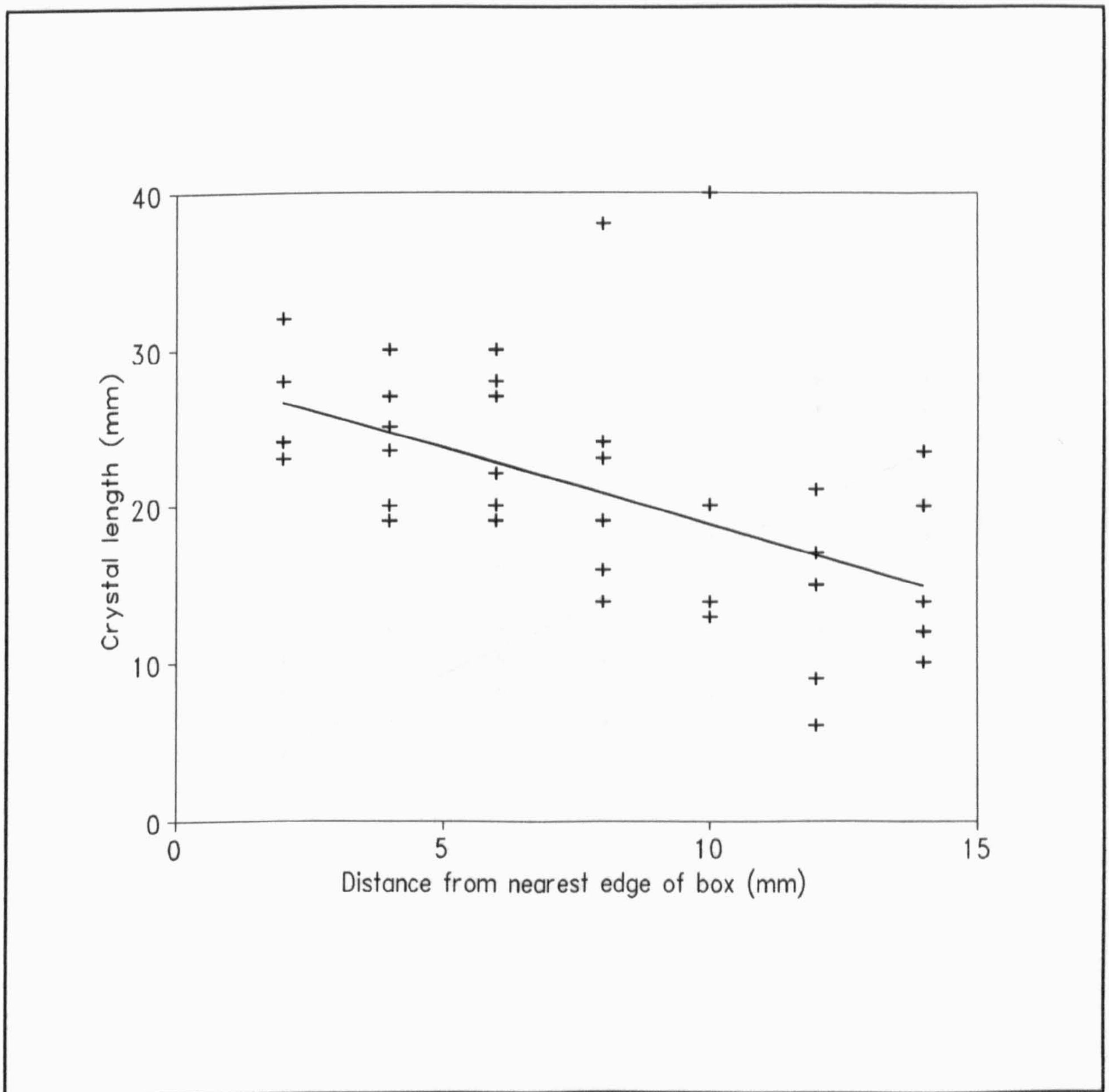

Figure 6.45 : USB_1; the relationship between distance from the nearest edge of the box and crystal length - saturated conditions

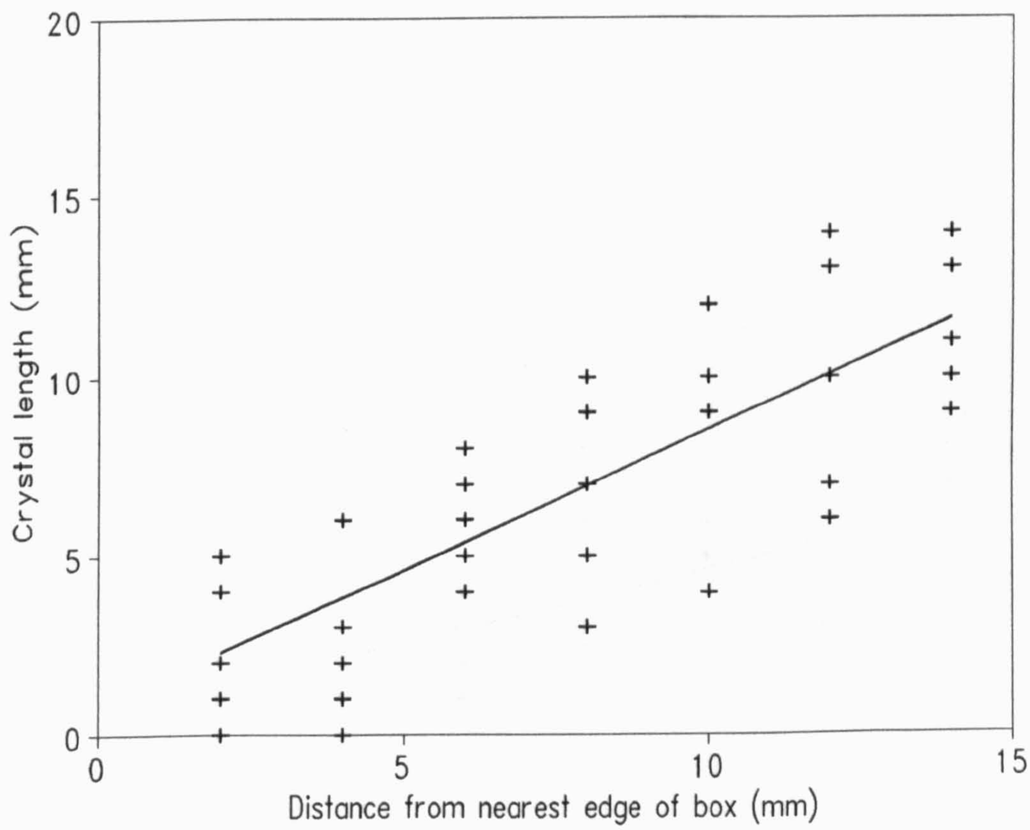

Figure 6.46 : DSB_1; the relationship between distance from the nearest edge of the box and crystal length - limited moisture content

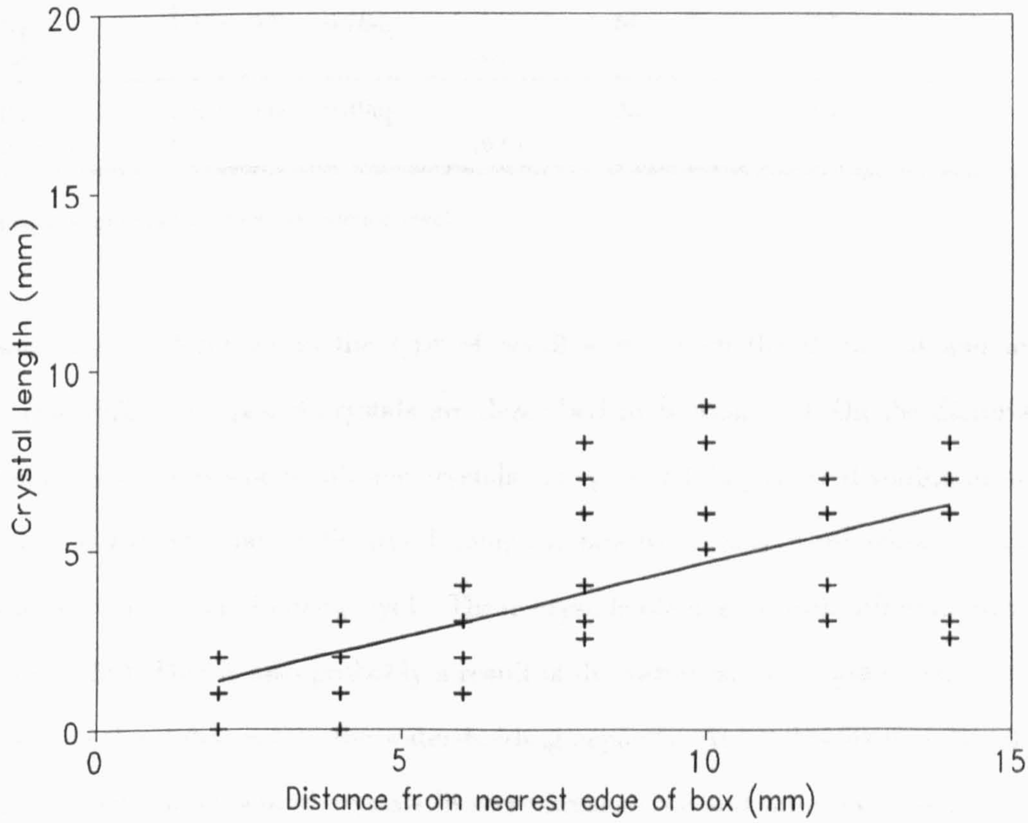

Figure 6.47 : USB_1; the relationship between distance from the nearest edge of the box and crystal length - limited moisture content

Table 6.5 : Regression relationship between distance from the nearest edge of the sample box and crystal length

Sample	Equation	R^2 (%)		St.error h-estimate (mm)	n
DSB_1 Saturated	$h = 18.17 - 0.18d_i$ (6.3)	2		5.1	42
USB_1 Saturated	$h = 28.29 - 0.96d_i$ (6.4)	28	*	6.2	42
DSB_1 Unsaturated	$h = 0.71 - 0.78d_i$ (6.5)	64	*	2.4	42
USB_1 Unsaturated	$h = 0.64 - 0.39d_i$ (6.6)	35	*	2.2	42

* indicates significant at 95% confidence level

There were also differences in the type of needles grown on the disturbed and undisturbed samples (the different types of crystals are described in Section 7.3). On the disturbed sample fewer differences in types of needle-ice crystals emerged and they showed similar growth profiles (e.g. Figure 6.49). On the undisturbed samples, however, there were often several types of crystals grown during one freezing cycle. These crystals often grew with different growth profiles (e.g. Figure 6.50). This is also probably a result of the variation in the grain-size characteristics of the soil and the difference in the water-holding capacity. At conditions near the threshold of needle-ice growth the growth of crystals in some areas of the soil was continuous whilst in other areas it was discontinuous. The uneven growth of needle ice over the surface of the undisturbed samples has implications for the erosion and transport of sediment by needle ice. These are discussed in Chapters 7 and 8.

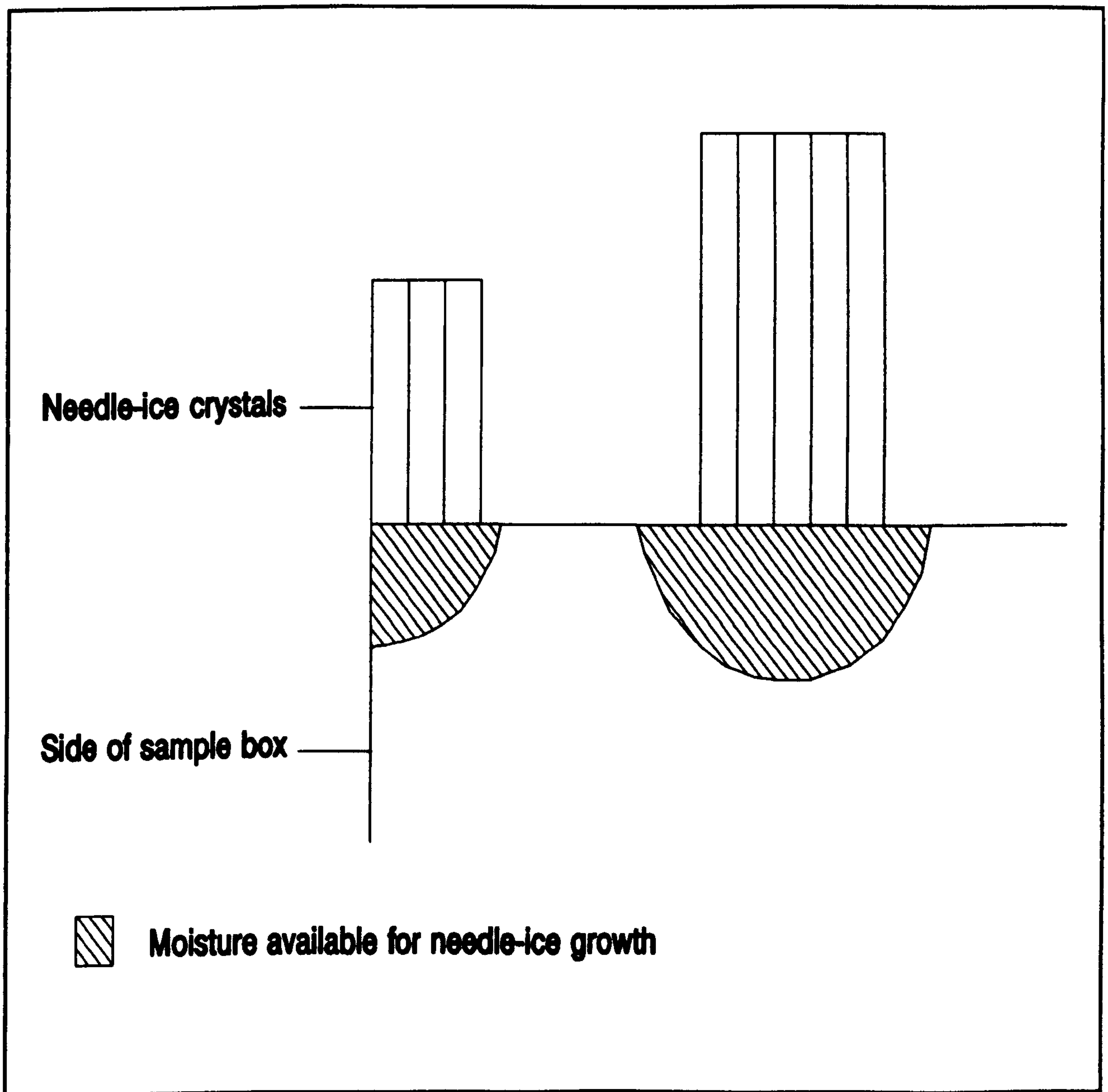

Figure 6.48 : The available contributing area of moisture for needle-ice growth from different areas of the soil sample

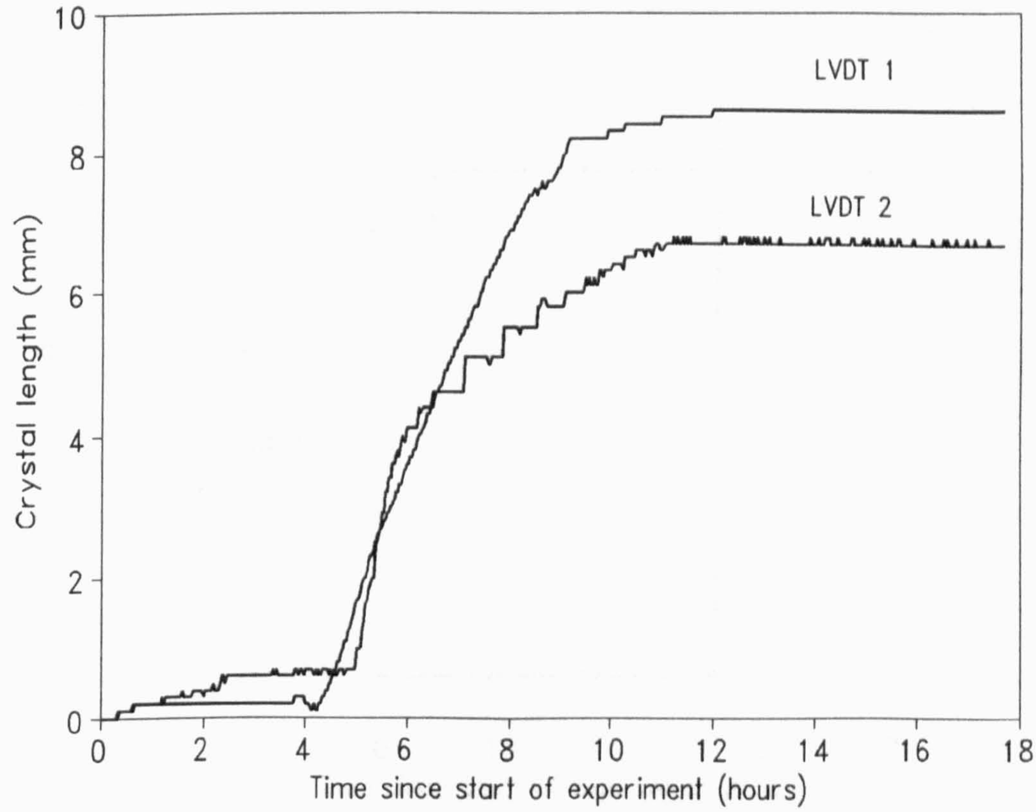

Figure 6.49 : Experiment 2/7/91; crystal growth profiles DSB$_1$

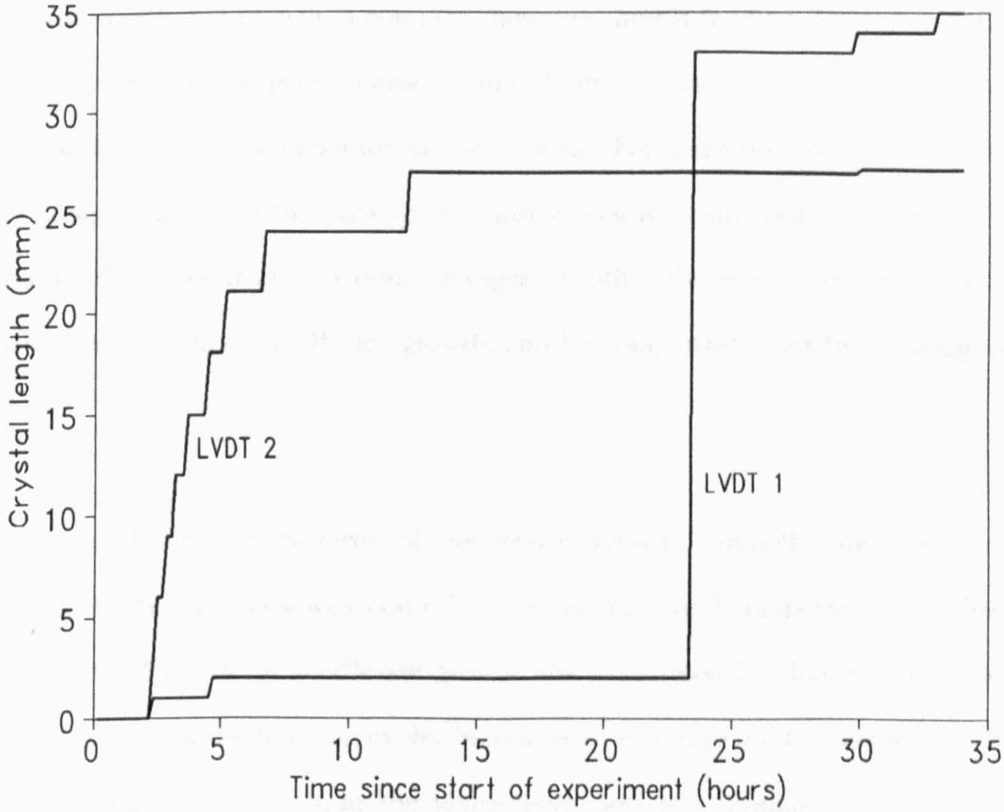

Figure 6.50 : Experiment 3/2/91; crystal growth profiles USB$_2$

6.5 CONCLUSIONS

This chapter has shown that soil-surface temperature and moisture supply are the main factors that control ice nucleation, ice segregation and thus needle-ice growth. The cooling rate of the soil surface is important and should be slow, ideally 0.5 to 1.5°C h^{-1}. Upper and lower limits of soil-moisture content have also been identifed.

The process of needle-ice growth is complex, however, and it is often difficult to separate cause and effect to determine the prime cause of the chain of events, e.g., whether changes in heat removal caused changes in moisture or vice versa. For example, the soil-moisture content influences cooling rate, and the cooling rate influences moisture migration. It is also possible that feedback effects occur and extreme changes in either the rate of heat removal or moisture content, which would affect needle-ice growth, can be compensated for by a change in the other factor.

There were two distinctive patterns of needle-ice growth: 'smooth' and 'intermittent'. The occurrence of the two profiles was controlled by mosture and temperature conditions during needle-ice growth. The rate of needle-ice growth was influenced by changes in temperature and moisture content during the freezing cycle. Increases in moisture content seemed to increase the rate of needle-ice growth, as long as the temperature was low enough.

There were differences in the range of crystal length and the continuity of needle-ice cover over the soil surface on the disturbed and undisturbed samples. The undisturbed samples showed the greatest variation. This is probably a result of the significant differences in the grain-size composition over the soil surface. The implications of the variations in growth with reference to sediment incorporation are discussed in Chapter 7.

This chapter has indicated that if the conditions required for needle-ice growth are not met then ice segregation may cease. Chapter 7 discusses how sediment can be lifted and incorporated by needle ice in the light of the above discussion on the processes that influence needle-ice growth.

Chapter 7

LIFT AND INCORPORATION OF SEDIMENT BY NEEDLE ICE

7.1 INTRODUCTION

Needle-ice crystals can either be clear or contain sediment (Section 3.2). Study of the sediment lifted and incorporated by needle ice is thought to be important in two respects:

i) it gives an indication of the growth history of the needle ice;

ii) the disturbance of the soil surface by needle ice results in soil erosion and may cause the formation of small landforms such as soil stripes (Section 1.3.2).

This chapter first describes the amounts, processes and patterns of sediment lift and incorporation by needle ice. In the second part of the chapter the characteristics of the lifted material in relation to the host material are examined. (Details of the downslope transport of material are reserved for Chapter 8 and the incorporation of sediment into needle ice is represented in a series of models in Chapter 9.)

The data presented in this chapter are summarised in Appendix 4.

7.2 AMOUNTS OF SEDIMENT INCLUSION BY DIFFERENT TYPES OF NEEDLE ICE

There were four ways by which sediment was lifted from the host sample (shown schematically in Figure 7.1 and also on Plates 7.1 to 7.5) (the precise definitions of terms (a), (b) and (c) are

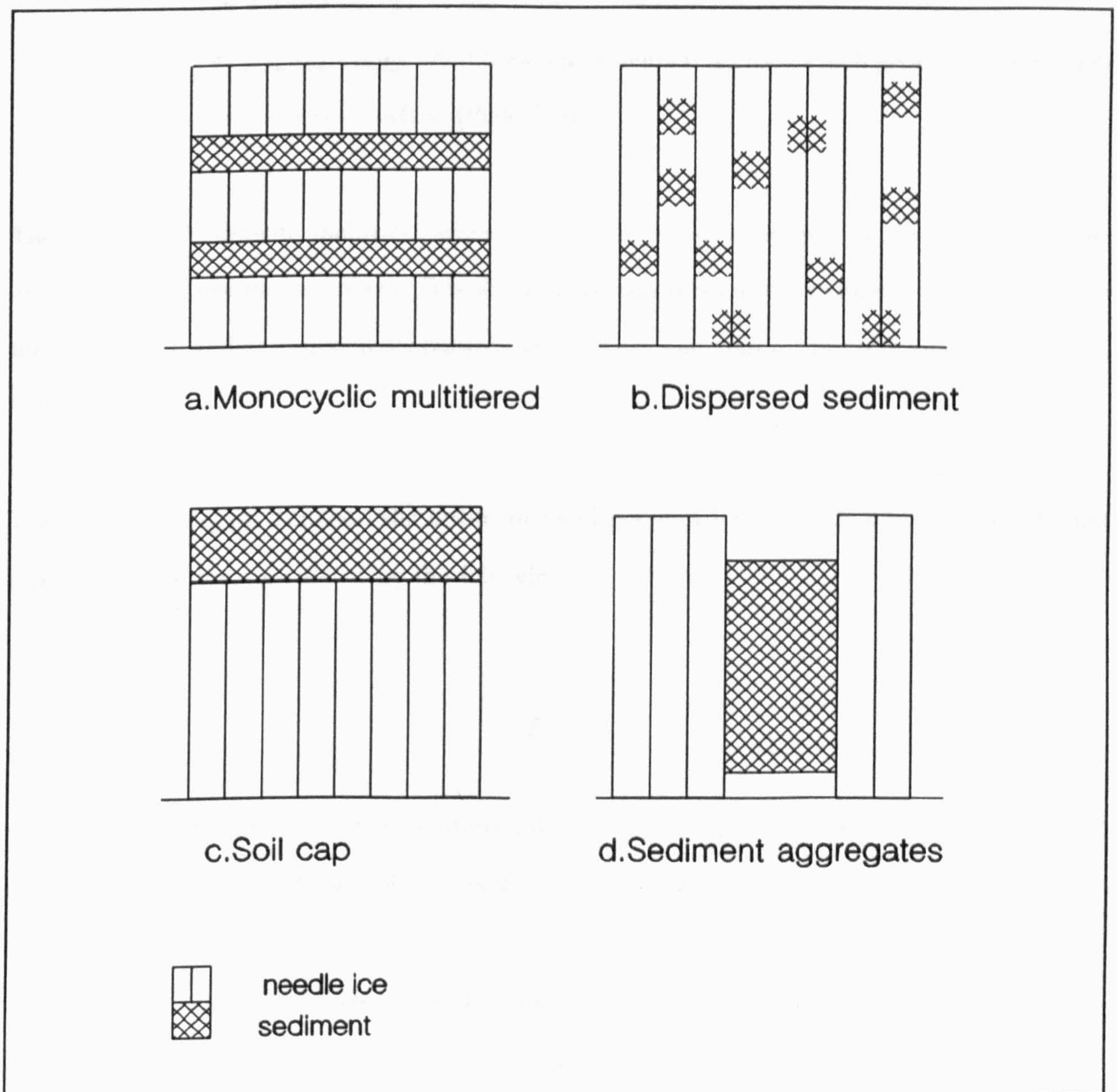

Figure 7.1 : Patterns of sediment inclusion in needle-ice crystals

given in Section 3.2.1):

a) as sediment layers within monocyclic multitiered ice crystals;

b) as dispersed sediment particles (Plates 7.3 and 7.4);

c) as a sediment cap (Plate 7.2);

d) as soil aggregates lifted between individual needles which grew discontinuously over the soil surface (Plate 7.5).

Each type of sediment inclusion seemed to occur when there was a disturbance in the environment of needle-ice growth. This disturbance was related to a reduction of moisture near the soil surface and/or a sudden decrease in soil-surface temperature, and is discussed in Section 7.3.

Table 7.1 and Figure 7.2 show the sediment yield per unit length of ice crystal from different types of needle ice, calculated by the following

$$E_c = \frac{E}{h} \qquad (7.1)$$

where E_c is the sediment yield per unit crystal length (g cm^{-3}), E is the sediment yield per unit area (g cm^{-2}) and h the height of the needle-ice crystal (mm).

Figure 7.3 demonstrates the contribution of individual needle types to the total sediment yield. Soil caps contribute the greatest amount of sediment to the total yield (c.85%), followed by sediment aggregates (7%). (The total sediment budget was calculated by adding the amount of sediment lifted from all the experiments; the individual percentages were calculated as the proportion of sediment contributed to the total by each type of crystal.) The large standard deviation of the sediment cap data is probably a result of the difference in the thickness of the sediment caps which in this study varied from c.2 mm to 15 mm. The dispersed and multitiered

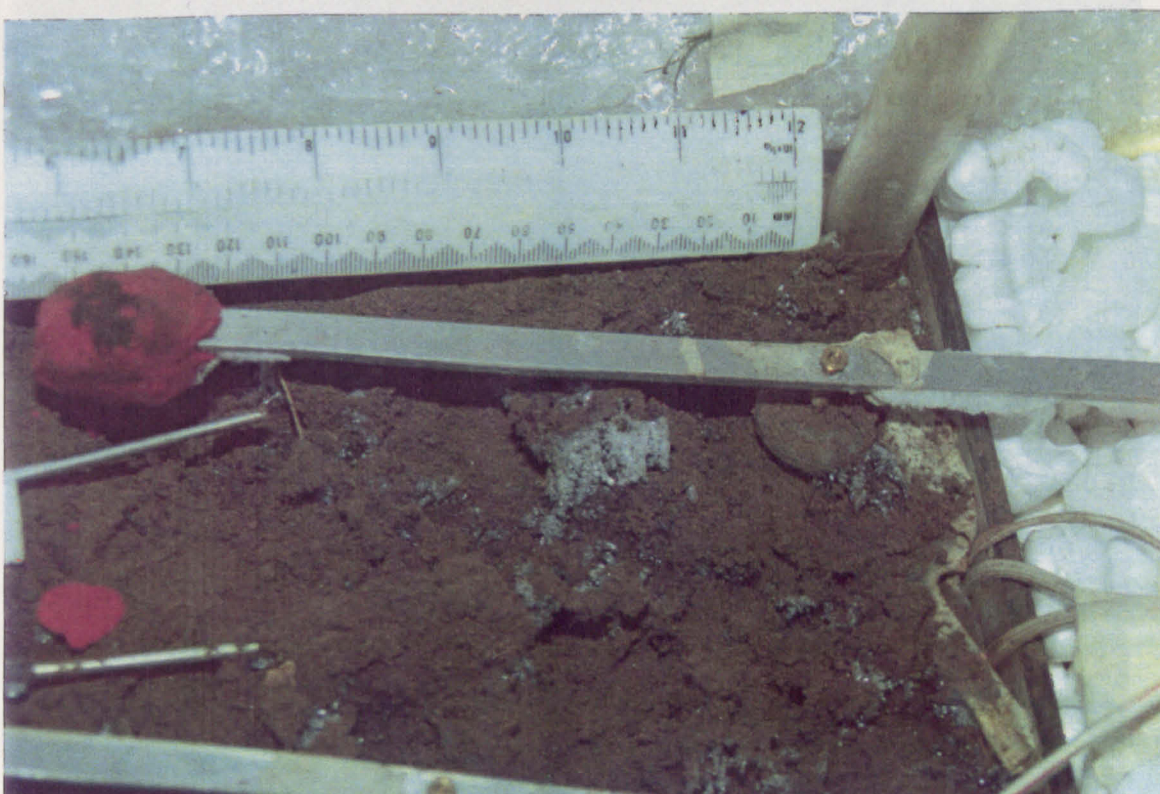

Plate 7.1: Clear needle ice
Plate 7.2: Needle ice with a soil cap

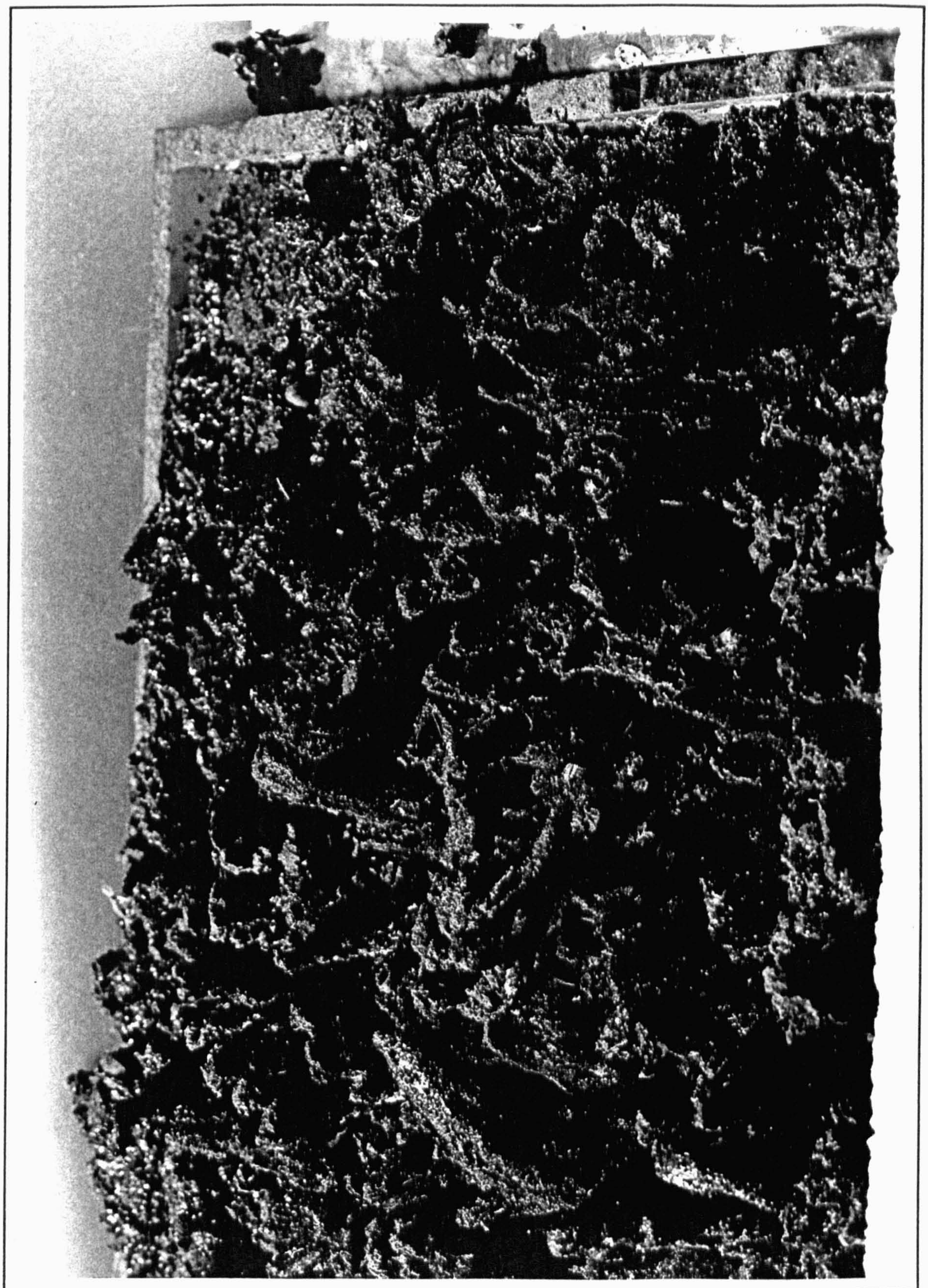

Plate 7.3: Needle ice with dispersed sediment and curved needle ice (right side of box is 20 cm long)

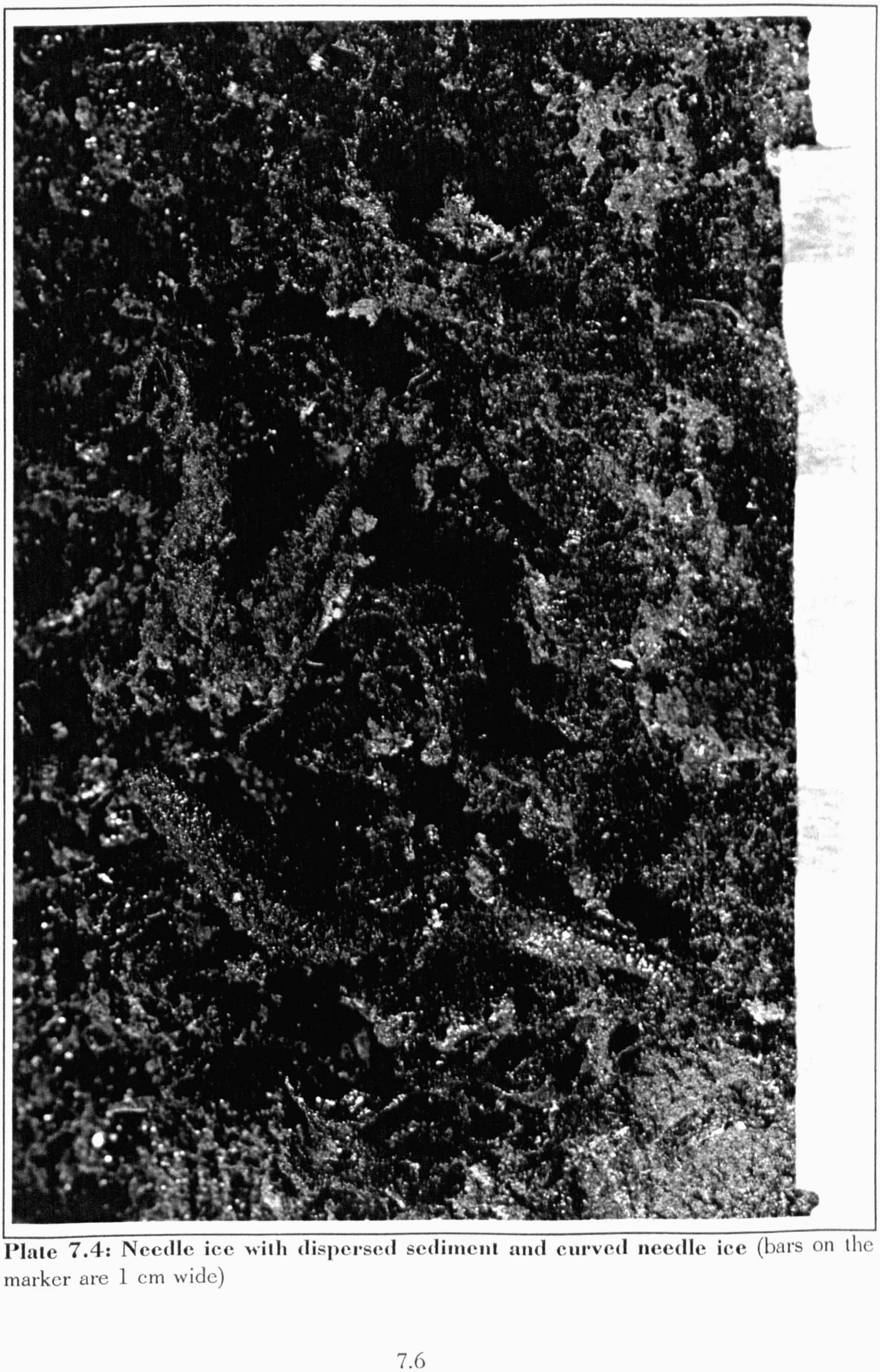

Plate 7.4: Needle ice with dispersed sediment and curved needle ice (bars on the marker are 1 cm wide)

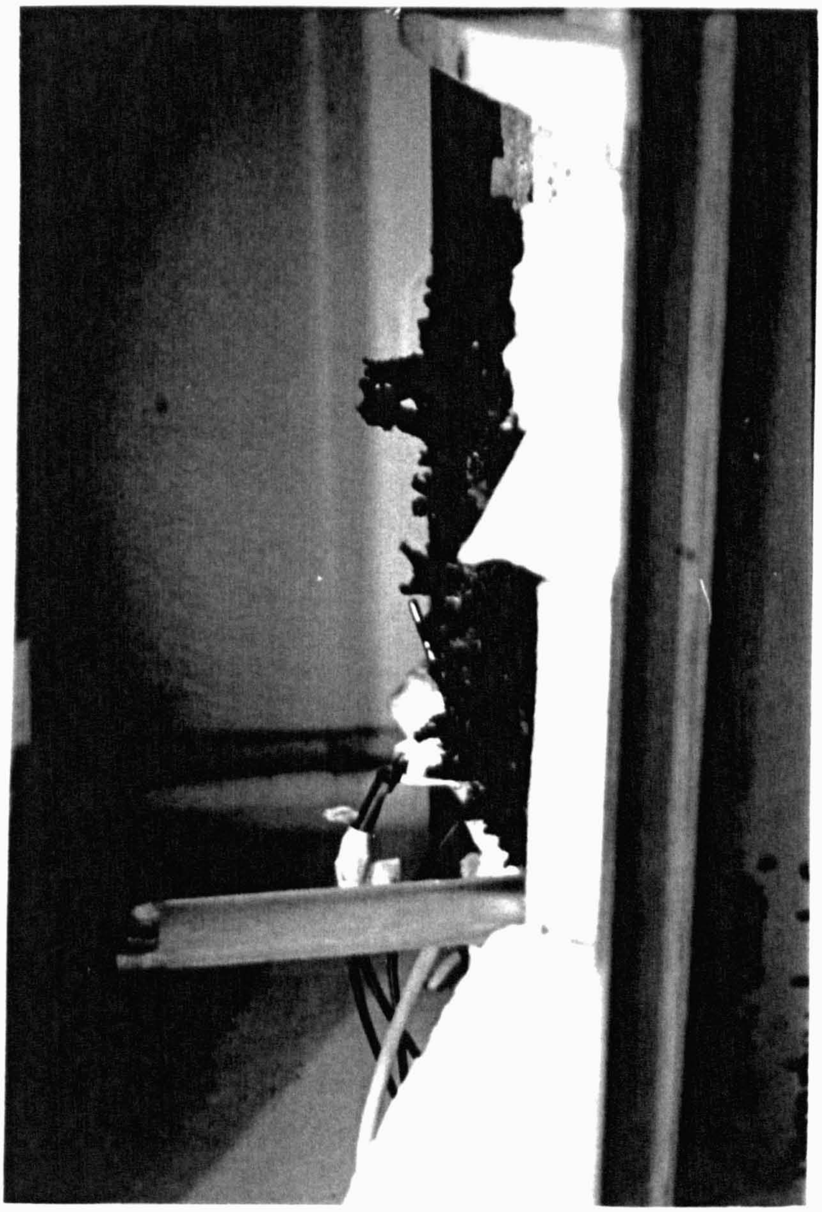

Plate 7.5: Needle ice that has grown unevenly over the soil surface and uplifted aggregates of sediment between the ice crystals

crystals contribute roughly the same amount to total sediment yield (4% and 3% respectively). Sediment was also lifted within needles that were classified as being 'clear', and this yielded c.1% of total sediment budget. This sediment was often frozen onto the base of the crystals, and this may explain the relatively high maximum sediment yield from clear crystals (which was greater than the minimum yield from the dispersed sediment). The sediment yields shown in Table 7.1 appear low when compared to the yields quoted from the fieldwork of other authors in Table 3.2, but it should be noted that the figures in Table 3.1 are expressed in terms of yield per unit area and not per unit of crystal length.

The relationship between the length of needle ice and sediment yield and the controls on the amount of sediment yield from the different types of crystal is investigated in further detail in Section 9.3.4.

Table 7.1 : The amounts of sediment uplifted by different types of needle-ice crystal

Needle type	Sediment yield per unit length of crystal (g)				n
	Mean	Minimum	Maximum	St. dev.	
Clear	0.005	0.0003	0.016	0.004	25
Dispersed sediment	0.028	0.005	0.079	0.015	49
Monocyclic multitiered	0.019	0.020	0.083	0.014	45
Aggregates	0.067	0.010	0.105	0.031	24
Soil caps	0.075	0.007	0.690	0.131	24

7.3 PROCESSES OF NEEDLE ICE SEDIMENT INCLUSION

Outcalt (1971a), in a detailed field study, determined that the morphology (or type) of individual needle-ice crystals varied according to the degree of incorporation of soil particles and the depth of the freezing plane. These differences were assumed to occur because of variability in energy

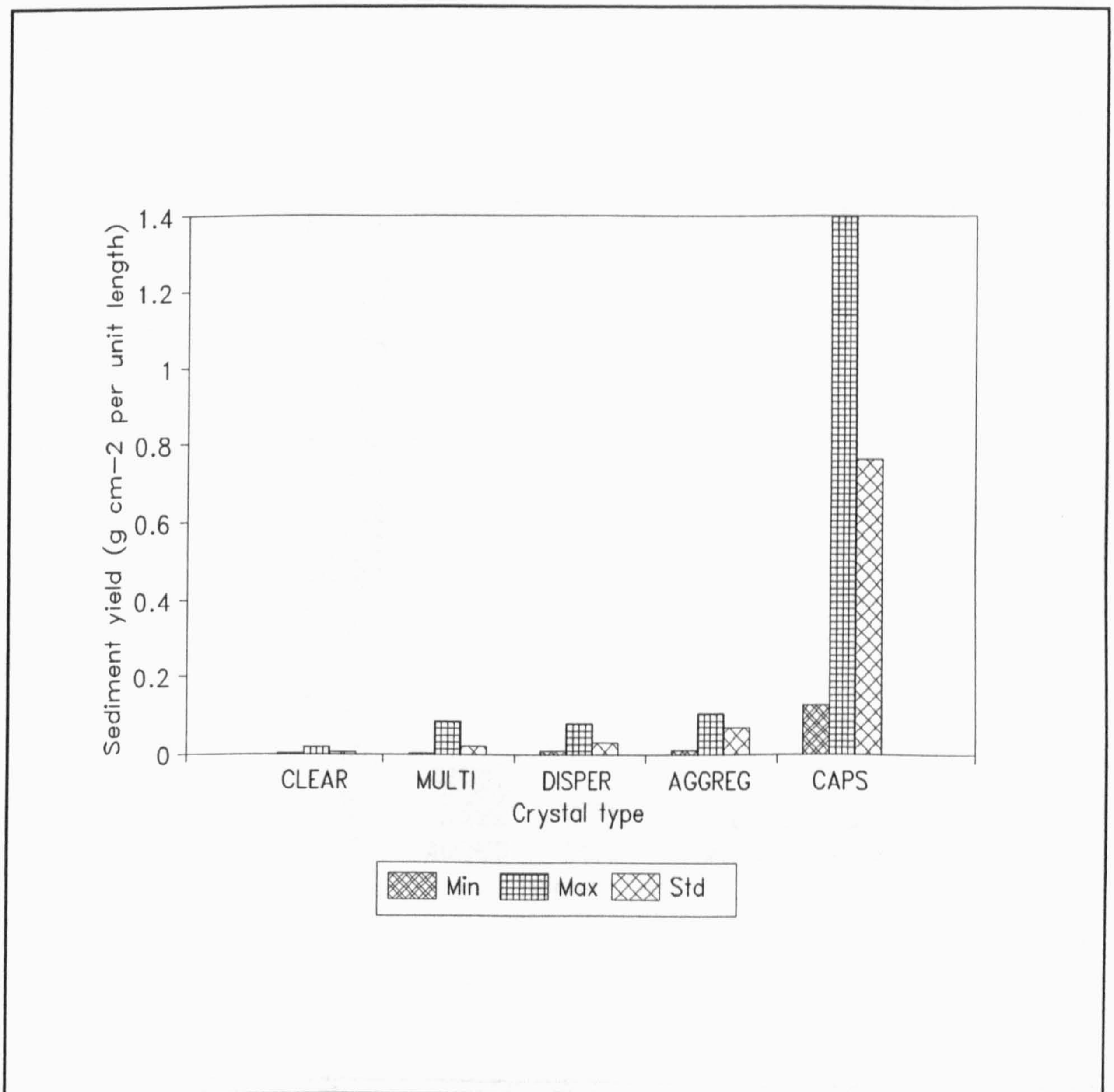

Figure 7.2 : Sediment yield from different crystal types **(all soil samples)**

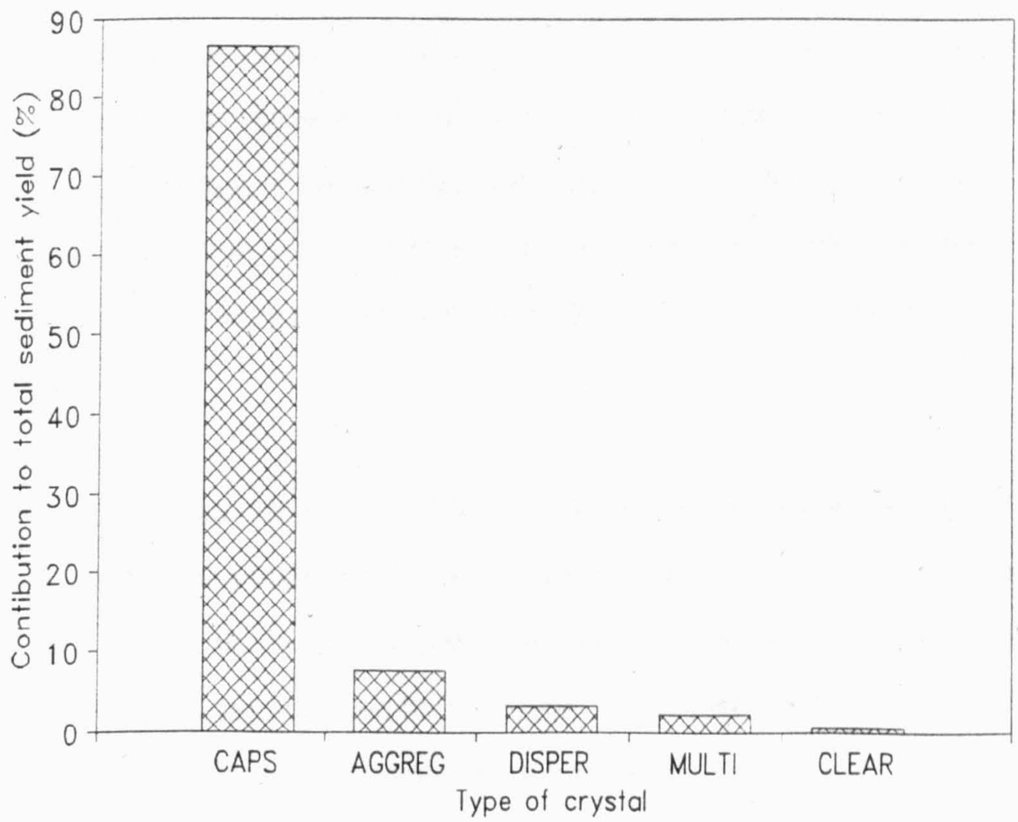

Figure 7.3 : The contribution to total sediment yield by different types of needle-ice crystal **(all soil samples)**

transfer and soil-moisture content at the soil surface. Recent advances in instrumentation have made it possible for the present study to investigate Outcalt's ideas experimentally.

7.3.1 Monocyclic multitiered needle ice-crystals: the process of sediment layering

Monocyclic multitiered ice-crystals (Section 3.2.2), are crystals that contain distinct layers of sediment (Figure 7.1a). In the present study crystals with up to six layers of sediment were observed.

The mechanisms by which monocyclic multitiered needles grew with an intermittent profile, but without soil banding, were described in Section 6.3.1. It was suggested that breaks in growth were a result of excess heat at the freezing front, caused by an influx of warm water. Contrary to this, it appears that needles which contained sediment layers were formed when there was too little heat arriving at the freezing front from below; data to support this argument are discussed in this section.

Fukuda (1936), Soons and Greenland (1970) and Outcalt (1971a) suggested that disturbances in the environment of needle-ice growth may cause sediment to be incorporated into the ice crystals (Section 3.2.2). In the present study this idea was tested by systematically disturbing the factors which are essential for needle-ice growth (i.e. soil-surface temperature, cooling rate and soil-moisture content). This was achieved in two ways:

i) allowing the soil-surface to freeze rapidly by using cooling curve E (Figure 5.10);

ii) limiting the supply of soil moisture to the freezing front by drying the sample or removing the water bath (Figure 5.1).

The growth profiles of the monocyclic multitiered crystals produced by either type of disturbance showed a similar shape (e.g. Figure 6.19).

7.3.1a Monocyclic multitiered crystals produced by temperature-limiting conditions. Cooling curve E (Figure 5.10) caused the soil-surface temperature to fall rapidly on two occasions during the freezing cycle (e.g. points A and B on Figure 7.4). When the moisture content just below the soil surface was c.25%-40% profile E produced ice needles that contained two sediment bands.

Figure 7.4 shows the data from a typical experiment where this occurred. The moisture content during the freezing cycle ranged between 29% and 40%. Sediment was incorporated into the needle ice on two occasions during the experiment (shown on Figure 7.4). This was verified by examination of the ice crystals after the experiment which showed that there were layers of sediment 7.75 mm and 9.5 mm from the base of the crystal (shown schematically at the right of Figure 7.4).

The plateaux in the growth profile seem to correspond with the periods when temperature at the soil surface decreased sharply. It is thought that at these points the increase in the rate of heat removal from the soil surface could not be compensated for by an increase in moisture flow (and associated heat from lower in the soil profile), and thus it appears that the freezing front descended into the soil profile. During the periods of freezing front descent no heave was observed at the soil surface. When the heat flow became balanced the soil-surface temperature increased and needle-ice growth recommenced.

Figure 7.5 shows data from another typical experiment where cooling curve E was used, but the moisture content remained above 40% throughout the freezing cycle. The profile of needle-ice growth is relatively smooth, and the ice crystals were composed of clear ice. In this experiment it appears that the moisture content (and thus the heat capacity, Section 2.3.2e) was sufficient to prevent the rate of heat removal from the soil surface from increasing when the soil-surface temperatures decreased. Thus, ice segregation continued throughout the freezing cycle.

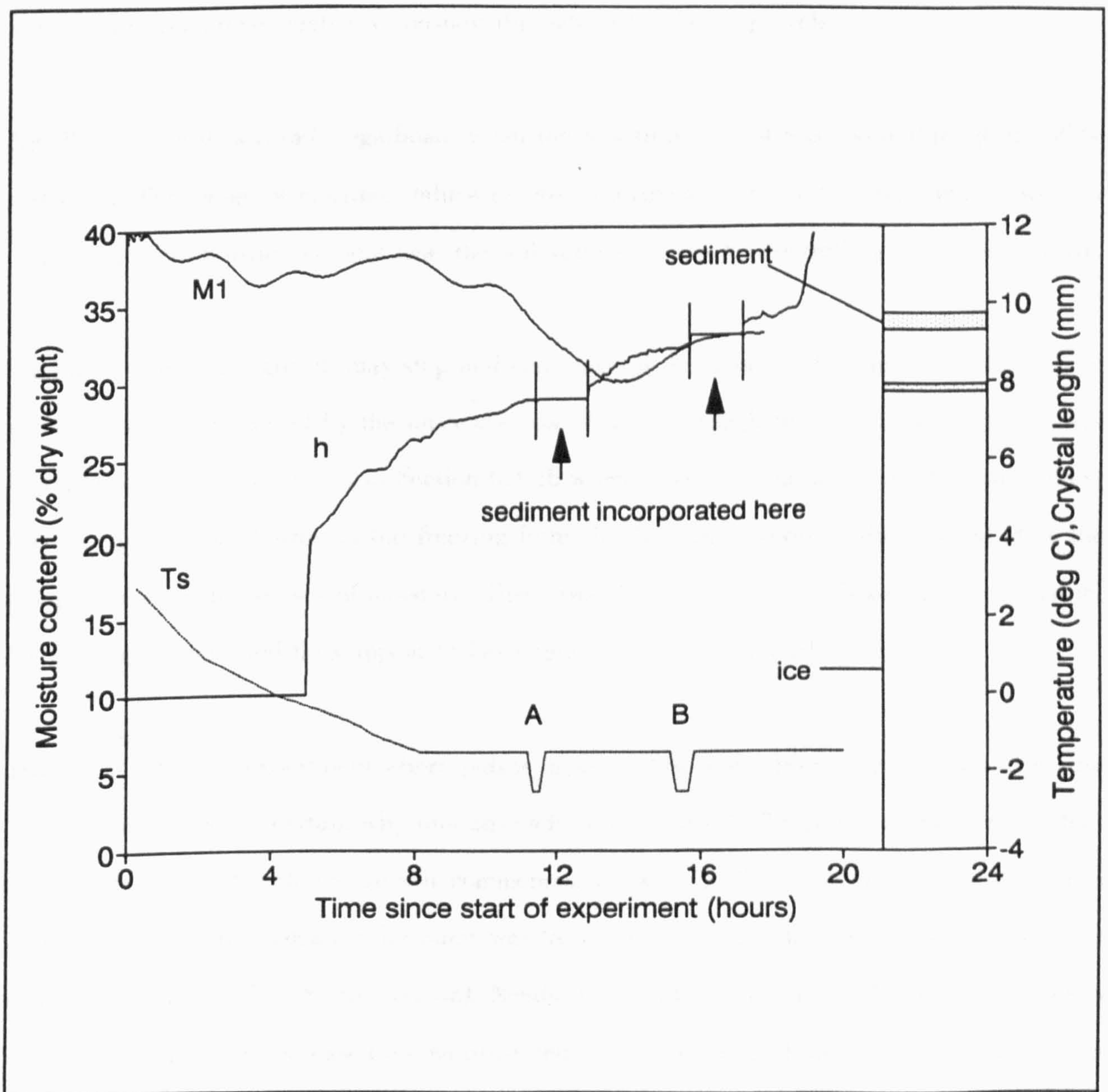

Figure 7.4 : Experiment 10/7/90; soil-surface temperature, moisture content and needle-ice growth USB$_1$

7.3.1b Monocyclic multitiered crystals produced by moisture-limiting conditions. Figure 7.6 shows needle-ice length and soil-moisture content near the soil surface during a simulation that produced needle ice with one sediment layer. In this simulation, moisture seemed to be the limiting factor because after the initial decrease in the nucleation temperature the soil-surface temperature remained relatively constant throughout the freezing cycle.

Needle-ice growth was only significant when the moisture content was rising through the 27% threshold. The range of moisture values in this experiment is not very large, and shows how critical the soil-moisture content near the soil surface can be for controlling needle-ice growth.

Similarly, needle-ice growth may stop and start several times in one freezing cycle as a result of moisture pulses caused by the unsteady flow of water through the soil profile. This process is analogous to that discussed in Section 6.3.2b where needle-ice growth ceased because there was too much heat flowing to the freezing front. In this case, however, the interest is in the troughs between the pulses of moisture. These troughs occurred at the lower limit of moisture for ice segregation, and thus appear to have caused needle-ice growth to cease.

Data from a typical experiment where pulses of water flow were observed are shown in Figure 7.7, although it is not certain why this unsteady flow occurred. The peaks in moisture content are labelled A-E. Needle-ice growth commenced at point 1. The moisture content started to decrease (presumably because the water was frozen into ice), and fell until it was at the limit of ice segregation (27%; Section 6.2.3a). Needle-ice growth then ceased. This probably caused in-situ freezing which increased the moisture tension in the soil and thus it appears that excess water was pulled towards the freezing front, evidenced by an increase in the moisture content. The moisture content increased to peak A and needle-ice growth recommenced at point 2 (Figure 7.7).

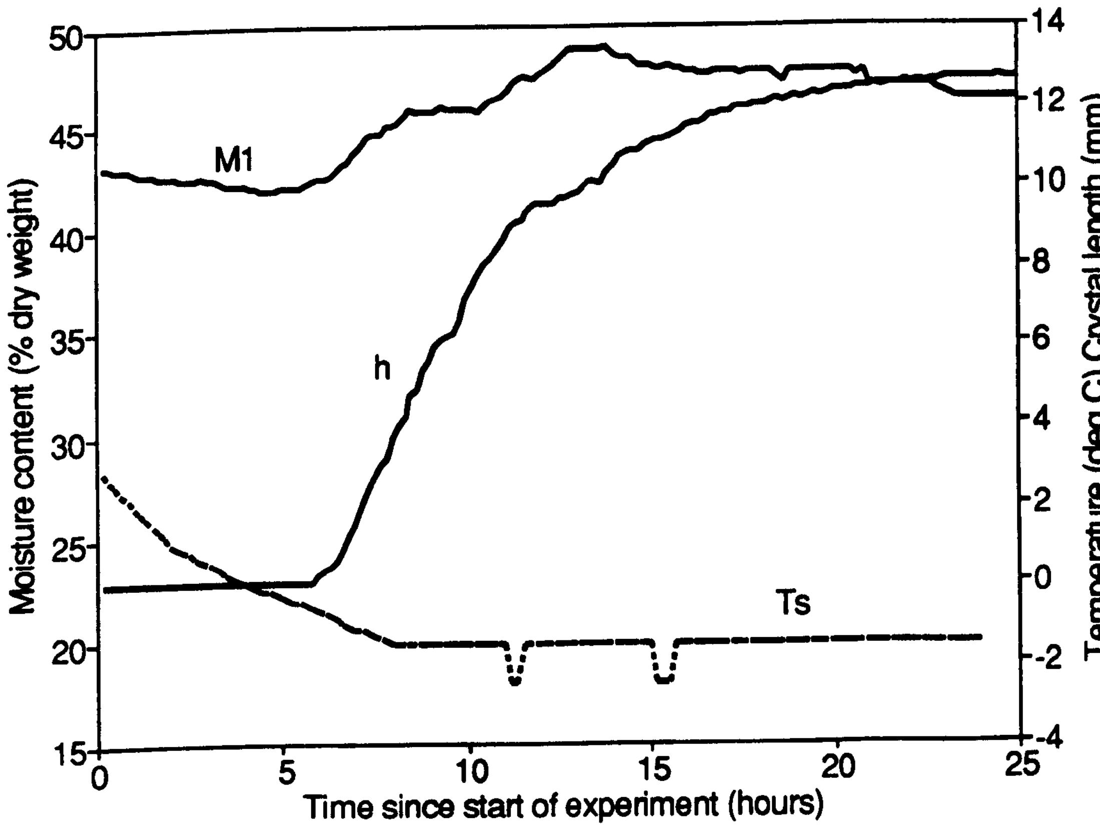

Figure 7.5 : Experiment 21/3/91; soil-surface temperature, moisture content and needle-ice growth **USB_1**

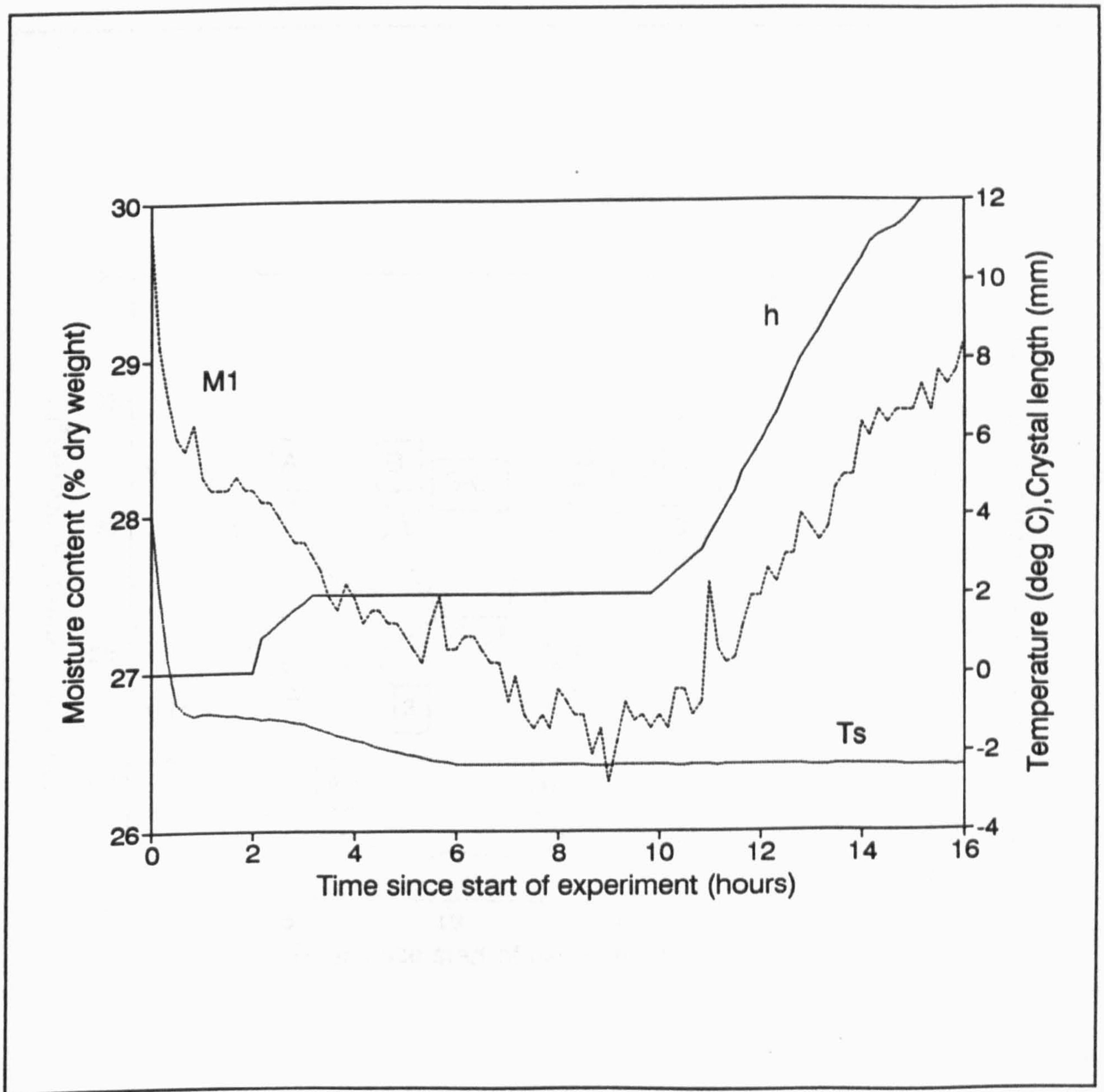

Figure 7.6 : Experiment 11/1/91; needle-ice length and soil-moisture content

USB_1

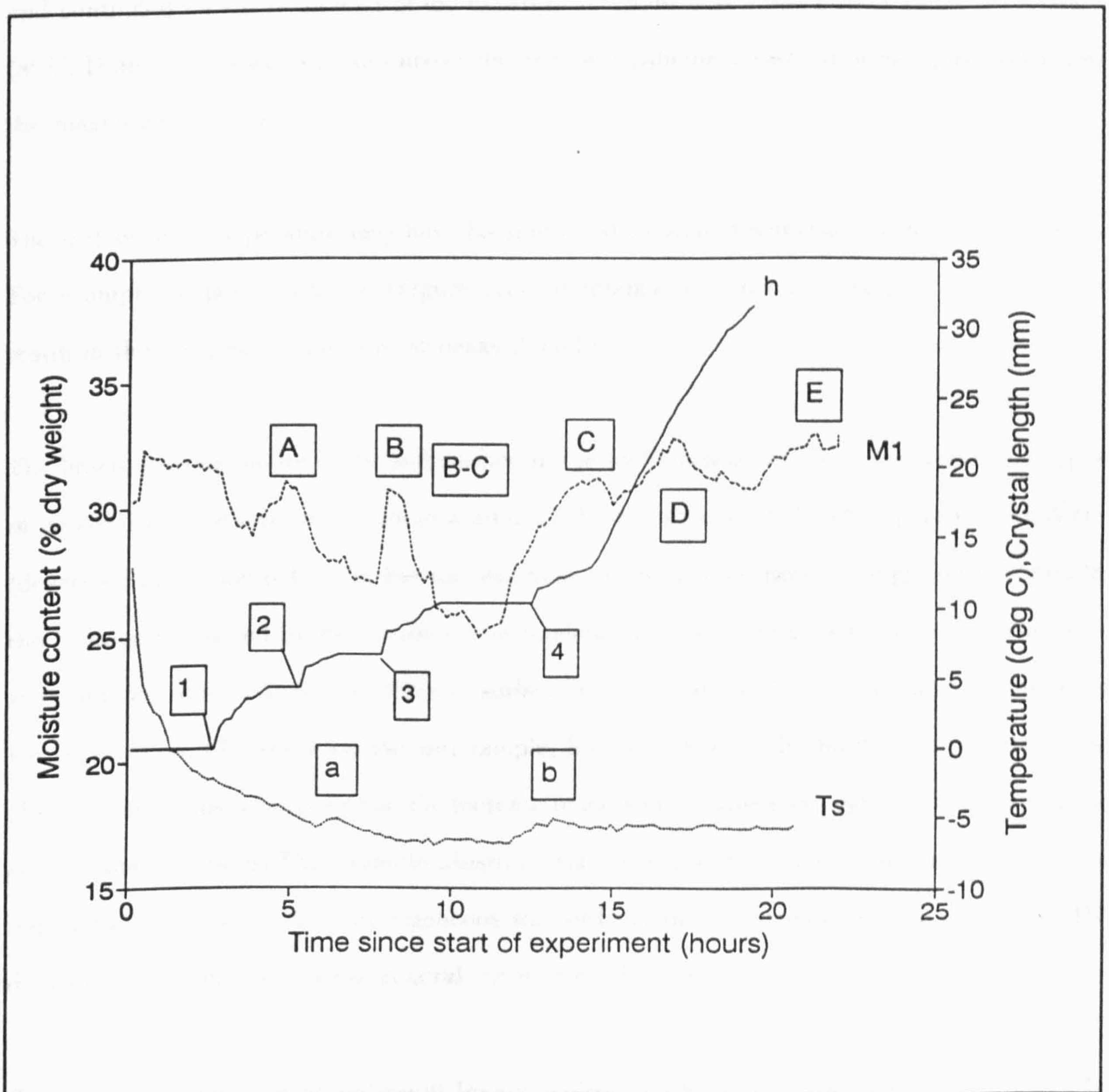

Figure 7.7 : Experiment 18/3/91; soil moisture pulses USB$_1$

After peak A it appears that the moisture supply became limited once again and needle-ice growth ceased. There was a further peak (B), which seemed to restart crystal growth (point 3). The moisture content then fell to 25% (point B-C) and growth ceased. Following this, the moisture content increased, crystal growth recommenced at 29.5% moisture content (point 4), and continued for the remainder of the experiment. There were three further peaks of moisture (at C, D and E), which occurred above the critical minimum threshold of moisture and below the maximum threshold.

The soil-surface temperature may have been affected by some fluctuations in moisture content. For example, at points a and b (Figure 7.7) the temperature increased slightly, possibly as a result of the increase in moisture at peaks A and C.

The heterogeneous nature of the soil surface in the undisturbed samples caused different types of needle ice to be formed on different areas of the soil (Section 6.4). In Experiment 11/2/91 (described in Section 6.3.3) the low soil-moisture content caused needle-ice growth to cease. In the location monitored by the displacement transducer, needle-ice growth did not recommence when the moisture content near the soil surface increased above the critical value required for ice segregation. Elsewhere on the soil sample, however, monocyclic multitiered needles were observed. It is thus postulated that the increase in moisture enabled ice segregation to start again only at some locations. This example illustrates the problems encountered when monitoring only one or two small areas of a heterogeneous soil surface. In most instances, however, the LVDT data were representative of the general cover of needle ice on the soil surface.

7.3.1c The formation of sediment layers within needle ice; a model based on Fukuda (1936) and Outcalt (1971a). Evidence presented above regarding the incorporation of sediment layers into needle ice is consistent with the theories of Fukuda (1936) and Outcalt (1971a) (Section 3.2.3b). It is suggested, therefore, that the following event sequence results in the formation of monocyclic multitiered needle ice (shown schematically in Figure 7.8):

i) the soil surface cools towards the ice nucleation temperature;

ii) when all conditions are satisfied needle-ice growth commences;

iii) the soil-surface temperature or moisture content becomes sufficiently low to disturb the heat balance at the freezing front. This causes the freezing front to descend and soil moisture is frozen in-situ;

iv) heat loss from the soil surface is reduced and/or the soil-moisture flow to the freezing front increased. This restores the heat balance and equilibrium conditions. The freezing front therefore becomes stationary and needle-ice growth recommences underneath the layer of frozen soil.

7.3.1d The association between the formation of ice lenses in soil and soil layers in needle-ice crystals. There may be an association between the processes by which soil layers are formed in needle ice and the formation of ice layers in frozen soil, although this connection does not appear to have been explored in the literature. When investigating the development of monocyclic multitiered ice crystals, however, it may be valuable to refer to the literature which discusses the formation of ice lenses. Martin (1959), for example, suggested that ice lenses in soil are formed as a result of the interrelationships between the phase change from water to ice, the mass transport of liquid to the freezing front and the unsteady flow of heat in freezing soil. He presented a four-stage cycle as a basis for a theory for ice-lens growth as follows (see also Hoekstra (1966), Horiguchi (1987), Penner (1986) and Williams and Smith (1989)):

i) nucleation of ice away from an existing freezing front;

ii) rapid growth of the nucleus into an ice lens;

iii) termination of crystal growth;

iv) heat and water flow between the end of (iii) and the beginning of a new cycle at stage (i).

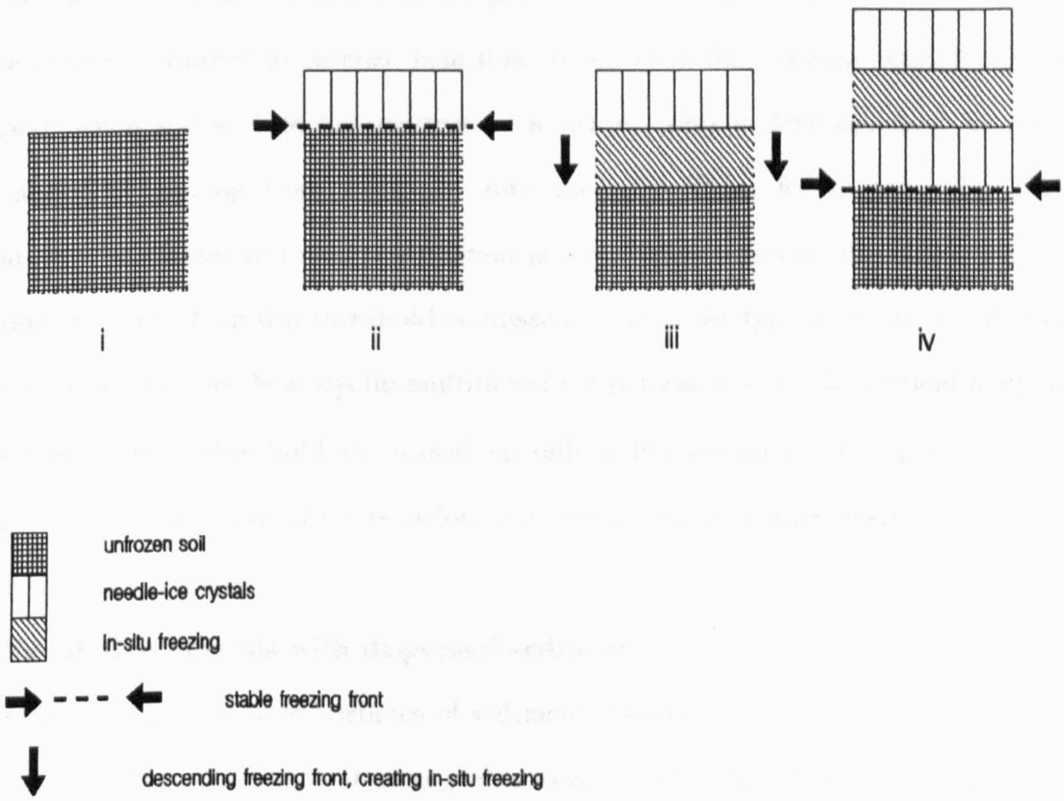

Figure 7.8 : The formation of monocyclic multitiered needle ice based on Fukuda (1936) and Outcalt (1971a)

This model is similar to that presented above for needle ice, given that when heat flow in the soil is unsteady the freezing front develops further down the soil profile. The incorporation of sediment into needle-ice would start at (iii) in Martin's model, however, with the termination of crystal growth.

Tagaki (1970) presented a similar argument to explain the development of ice lenses in soil. He stated that formation of ice lenses is a problem of the simultaneous flow of heat and water within certain boundary conditions. For needle-ice growth the boundary conditions are the critical soil-moisture content required to balance heat flow to and from the freezing front. If this boundary is 'crossed' when soil-surface temperature or moisture content decrease then in-situ freezing occurs and the freezing front descends into the soil. Thus, for a particular soil-surface temperature a particular soil-moisture content is required to maintain the balance of heat flow. The frequency with which this threshold is crossed controls the type of needle ice that is formed in a given freezing event. Monocyclic multitiered ice is formed when the critical temperature or soil-moisture content threshold is crossed on only a few occasions during an event. (In-situ freezing may occur for several hours before ice segregation recommences.)

7.3.2 Needle-ice crystals with dispersed sediment

Some needle-ice crystals have particles of sediment distributed throughout them, giving the ice a brown colour (Figure 7.1b); sediment yields were found to be similar to multitiered crystals (Table 7.1). The processes described above with reference to multitiered ice seem also to result in the formation of needle-ice crystals with dispersed sediment, although the disturbance to the balance of heat flow appears to be at much smaller temporal and spatial scales.

The results of the present study agree with the observations of Outcalt (1971a and Section 3.2.3c), who suggested that crystals with dispersed sediment are formed when areas of ice segregation are separated by areas of in-situ freezing. The incorporation of individual particles of sediment into needle-ice crystals in the present series of experiments occurred when soil moisture and temperature conditions were at the threshold between growth and no-growth. Growth is believed to have stopped and started when conditions continually cross the critical moisture/temperature threshold by the processes described in 7.3.1. In-situ freezing only occurred for a very short period and the freezing front probably descended only a fraction of a millimetre. This process has been difficult to quantify, however (Section 9.3).

Figure 7.9 shows soil-surface temperature, moisture content and needle-ice growth for a typical experiment which produced needle ice with dispersed sediment. The growth profile is similar to those produced during the growth of clear ice (e.g. Figure 6.1); thus, from the growth data alone, it is not possible to determine the type of crystal produced. The dispersed sediment needles, however, were formed at lower soil-surface temperature and moisture contents than clear crystals. The moisture content declined from 31% to 27.5% during freezing and when combined with a soil-surface temperature of -6°C, seems to have brought about threshold conditions between growth/no growth. It appears that ice segregation must have stopped frequently during the freezing cycle (Figure 7.9), and caused the freezing front to descend into the profile, thus incorporating sediment into the ice. This probably occurred at timescales too short to be identified by the LVDT data, however (recorded every 2 minutes in the second stage experiments (Section 5.2)). Several experiments were carried out which recorded the data at 30 s intervals and these did not show any disturbance to growth either.

7.3.3 Sediment caps

This section discusses the lift of sediment as a cap on the top of needle-ice crystals (Figure 7.1c). Sediment caps were responsible for 85% of total sediment yield disaggregated by needle ice. Two types of sediment cap were produced in the present study: frozen and unfrozen.

No soil caps were produced on top of the ice needles that were grown during the preliminary study. This is because after the water was added to the soil surface the sample was covered to allow it to equilibrate (Section 5.3.1). Thus, there was no evaporation from the soil surface before

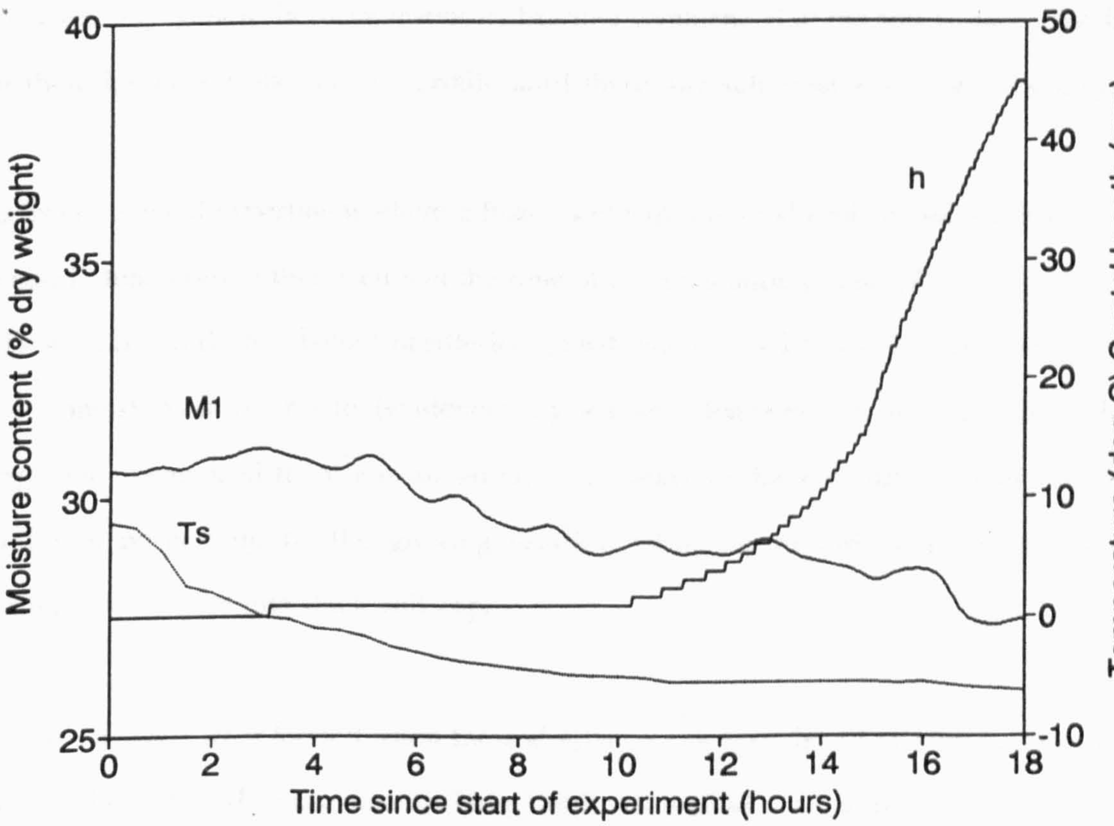

Figure 7.9 : Experiment 8/7/91; the formation of dirty needle ice USB$_1$

freezing commenced: in a field situation, however, evaporation will occur. In some of the second stage experiments, therefore, a heat lamp was used to dry the soil surface. After the sample was dried it was necessary to leave it to cool before subjecting it to a freezing cycle, otherwise there was residual heat at the soil surface which affected the cooling of the sample (Section 6.2.3a).

Frozen soil caps were produced when the soil surface moisture content at the start of the experiment was between 15% and 28%. Here, there was sufficient moisture for ice nucleation but not ice segregation. In these instances freezing commenced at the soil surface. The freezing front then descended into the soil profile until there was sufficient water for ice segregation.

Data from a typical experiment where a frozen soil cap was produced are shown in Figure 7.10. The rise in temperature that occurs at the time of ice nucleation (Figure 7.10, point A) (Section 6.2.1) was observed 16 h before needle-ice growth commenced (point B). After ice nucleation the soil moisture froze in-situ (evidenced by sub-zero temperatures at T_1). Thus, when ice segregation commenced there was an initial rapid heave of the soil surface as the frozen layer of soil was pushed up by the growing needles. Clear ice crystals were produced in this experiment with a 10 mm thick soil cap.

Unfrozen soil caps were formed when the soil surface was very dry (3 to 15% surface moisture content at the start of the experiment). Thus, there was limited water available for ice nucleation. The freezing front therefore probably developed below the soil surface where there was sufficient water available for ice nucleation, indicated by the sub-zero temperatures in the soil profile (at T_1) (Figure 7.11). When needle-ice growth commenced, therefore, a desiccated cap was pushed up on top of the needles. This experiment produced clear needles with a 5 mm thick soil cap.

The location of the freezing front regulates the amount of soil lifted from the sample (Meentemeyer and Zippin, 1981). The lower down in the soil that the freezing front forms, the thicker the soil cap produced. In this respect the thermal and moisture gradients near the soil

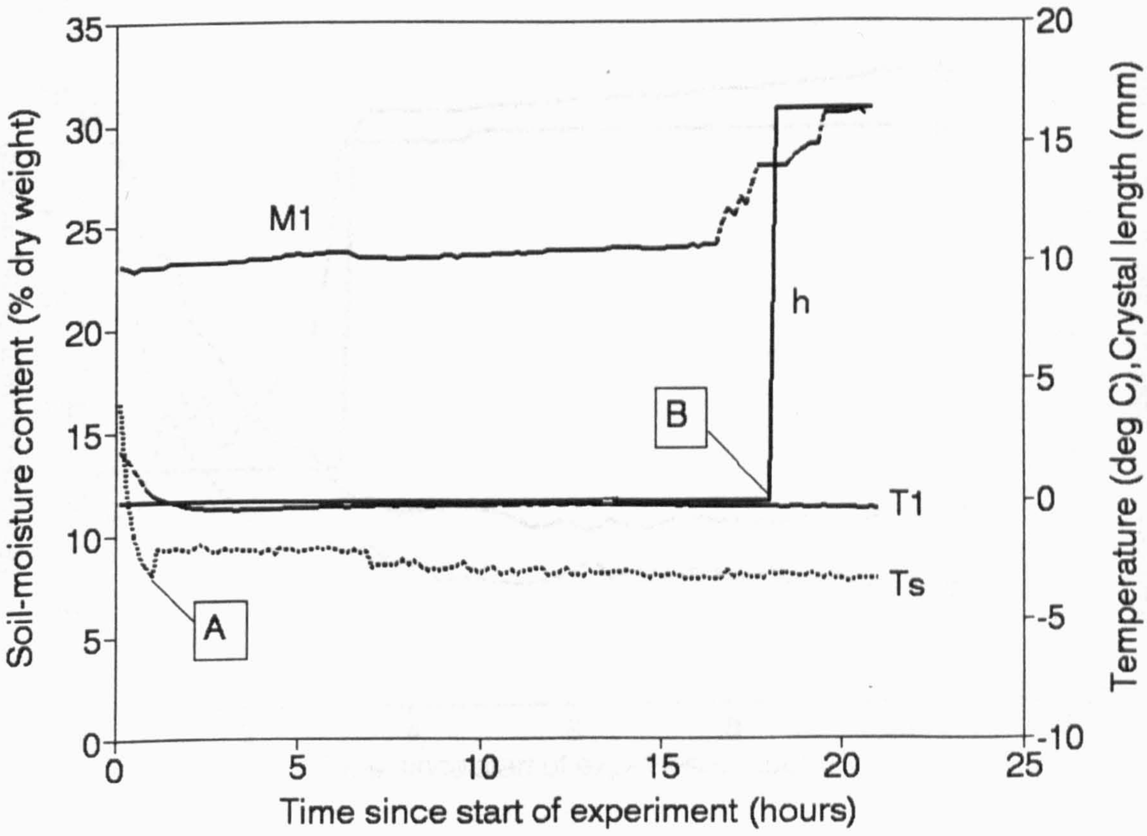

Figure 7.10 : Experiment 8/11/90; the formation of a frozen soil cap USB$_1$

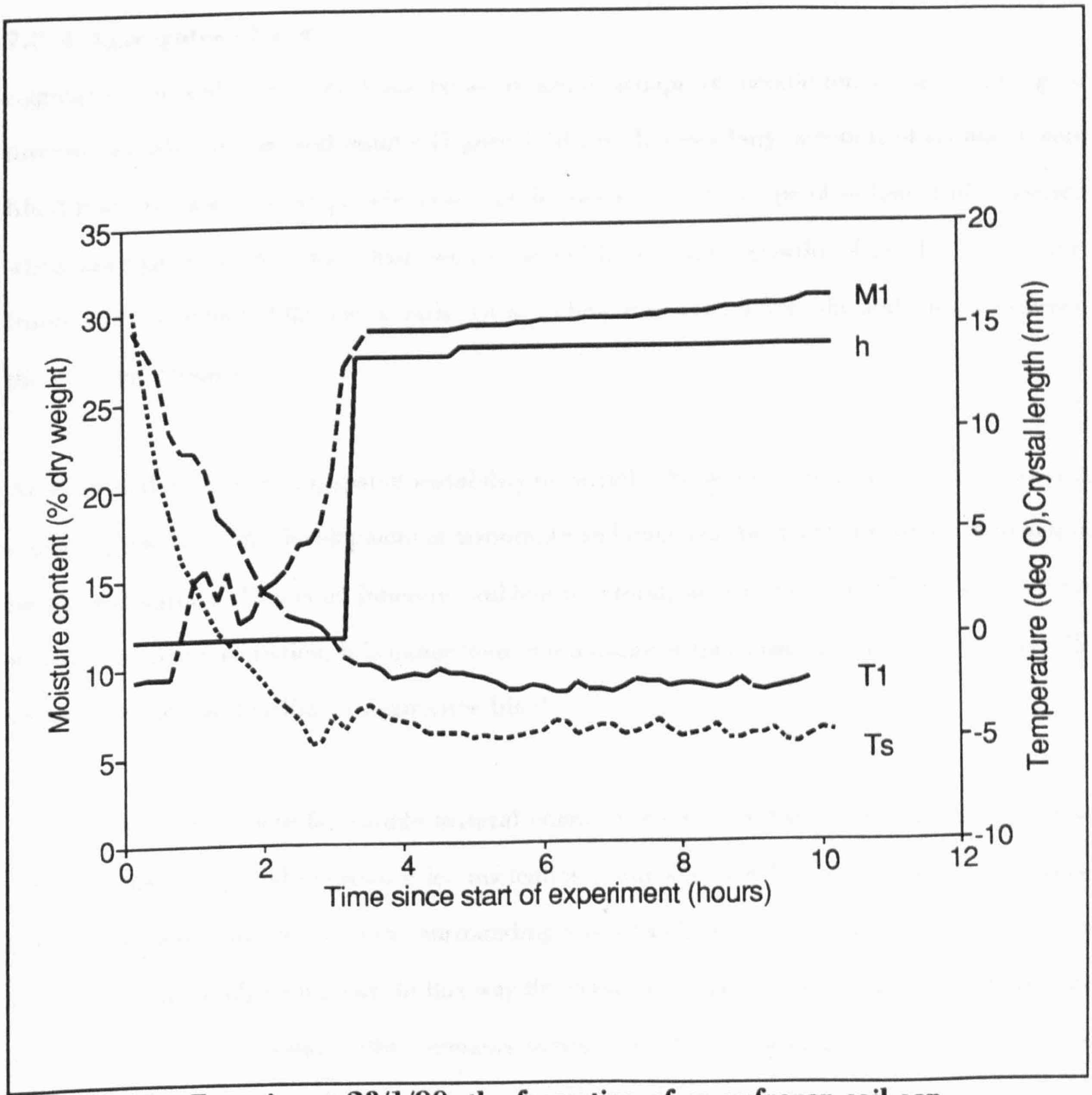

Figure 7.11 : Experiment 23/1/90; the formation of an unfrozen soil cap

USB$_1$

surface at the time of ice nucleation are very important. If the gradients are very gentle then it is expected that a large thickness of soil will be frozen. Thus, when the conditions for ice segregation are met a thick soil cap will be pushed up by the needles.

7.3.4 Aggregates of soil

Aggregates of soil were lifted up between small groups of needle-ice crystals that grew discontinuously over the soil sample (Figure 7.1d). In this way large amounts of sediment were lifted from the host soil sample (Section 7.1). It appears that this type of sediment lift occurred when aggregates of soil which had been loosened by previous growths of needle ice became frozen onto the edges of the ice crystals. Thus, sediment was lifted from the soil surface between the growing crystals.

As suggested in Section 6.4, spatial variability in particle characteristics (and thus water-holding capacity) results in the development of favourable and unfavourable locations for ice segregation on the soil surface. This is an inherent problem if natural, undisturbed soil blocks are used for this type of experimentation. It is under these circumstances that a discontinuous cover of needle ice is produced and sediment aggregates lifted.

Where the soil has more favourable textural characteristics, or a higher moisture content, less supercooling is required to produce ice nucleation (Shumskii, 1964). The crystals that nucleate first may be a moisture sink for the surrounding area of soil, and seem to prevent ice nucleation from occurring in adjacent areas. In this way the crystals can grow to a considerable length. The region between the crystals either remains unfrozen or freezes in-situ. As the crystals grew, sediment was lifted between them.

It was illustrated in Section 6.4 that the grain-size composition of sample USB_1 varied over small distances, whereas on sample DSB_1 the particle-size distribution was more uniform. This may explain why, under ideal growth conditions, a dispersed cover of needle ice was observed frequently on the undisturbed sample but rarely on disturbed soils.

In conditions where the moisture content was limited, the growth of dispersed needles was common on both sample USB_1 and DSB_1. This can be illustrated by the density of ice produced per unit area on soils with different moisture contents (Figure 7.12). There is a weak positive relationship between the moisture content of the soil surface at the start of the experiment and the density of the needle ice. All types of needles were included in the analysis and this may explain the variability of the data in Figure 7.12 (for example, a clear crystal and multitiered crystal of the same length may contain slightly different amounts of ice). From this analysis it is apparent that lower moisture contents encourage more dispersed ice crystals and there is probably a greater potential area from which aggregates can be lifted (this is explored in further detail in Section 9.3.3e).

Soons and Greenland (1970) also determined that needles become less dense with successive growth and melt cycles as a result of reductions in the soil-moisture content. In the present study it appeared that preferential growth of needle ice occurred during freezing at intermediate and low soil-moisture contents, which caused the development of a discontinuous cover of crystals.

7.4 GRAIN-SIZE DISTRIBUTION OF HOST AND INCLUDED MATERIAL

Soils affected by frost action often exhibit distinctive sorting patterns. These features can be macroscopic (e.g. patterned ground: polygons, stone stripes (Section 1.3)) or microscopic (small-scale variations within the soil profile) (Van Vliet-Lanöe, 1985). Van Vliet-Lanöe (1985; pp.125-126) argued that 'stone lifting and expulsion from the soil is characteristic of all frost-susceptible soils and results from a sequence of processes acting in freezing soils'.

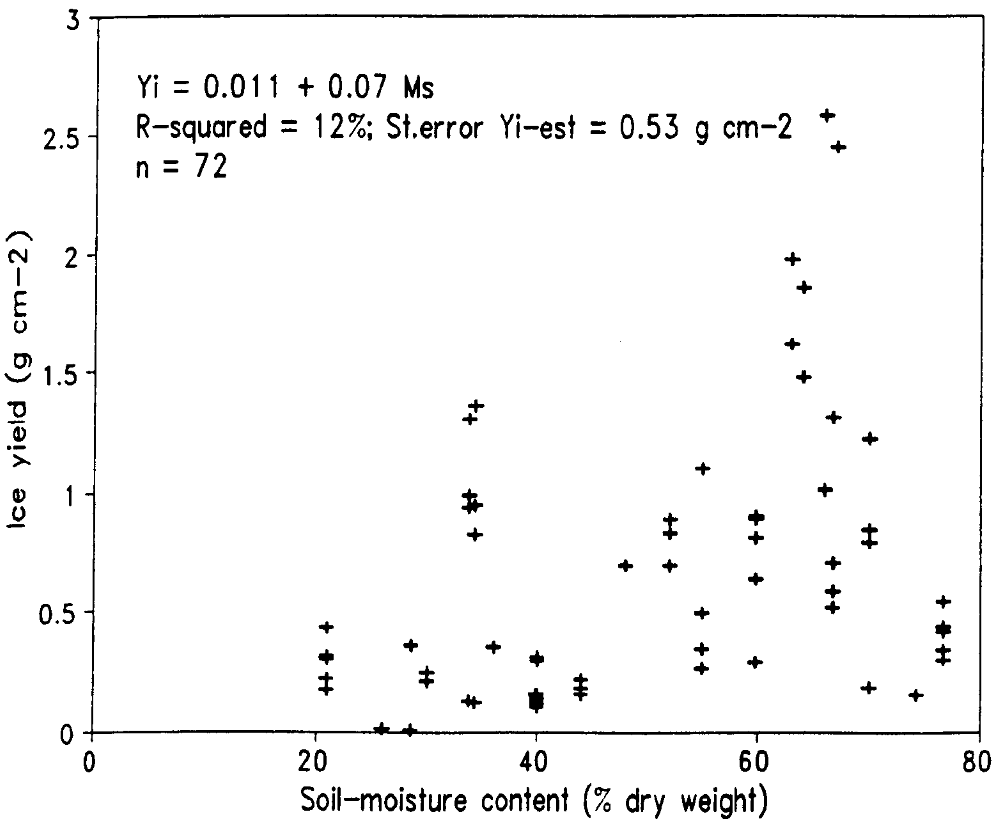

Figure 7.12 : Density of ice produced with different soil-moisture contents (the data were standardised to give values per unit length of ice crystal)

USB$_1$

In this section the sorting of material by needle ice is investigated. Comparisons are made between the grain-size distribution of the soil from which the needle ice grew (the bulk material) and the sediment incorporated into the needle ice.

From laboratory experiments Meentemeyer and Zippin (1981) determined that there was no significant difference between the grain-size distribution of the bulk soil sample and the sediment that was included within the needle-ice crystals. Thus, they expected that needle ice would lift any available material. The present study, however, based on both laboratory and field data showed that the included material was significantly coarser than the host material. Three examples are presented in this section.

Figure 7.13 shows the grain-size distribution of the host and included material from sample USB_1 (laboratory experiments) and Figures 7.14 and 7.15 from samples of needle ice which grew under natural conditions in two field sites. (Both field sites were located in Selly Oak, Birmingham, and the needle ice grew in January 1991. Field data were collected to test the possibility that some aspect of the laboratory procedures had caused the included material to appear coarser.)

These figures show that at grain sizes less than around 0.3 to 0.4 mm the host and included sample curves diverge. Summary statistics of the data from Figures 7.13, 7.14 and 7.15 are given in Table 7.2. These data show that at all indexes of grain size the included material is coarser than that of the bulk sample (with the exception of D_{25} on USB_1 where the materials have the same grain size). The incorporated and parent materials for each sample were compared with a T-test. For all samples the bulk and incorporated material had a significantly different particle distribution.

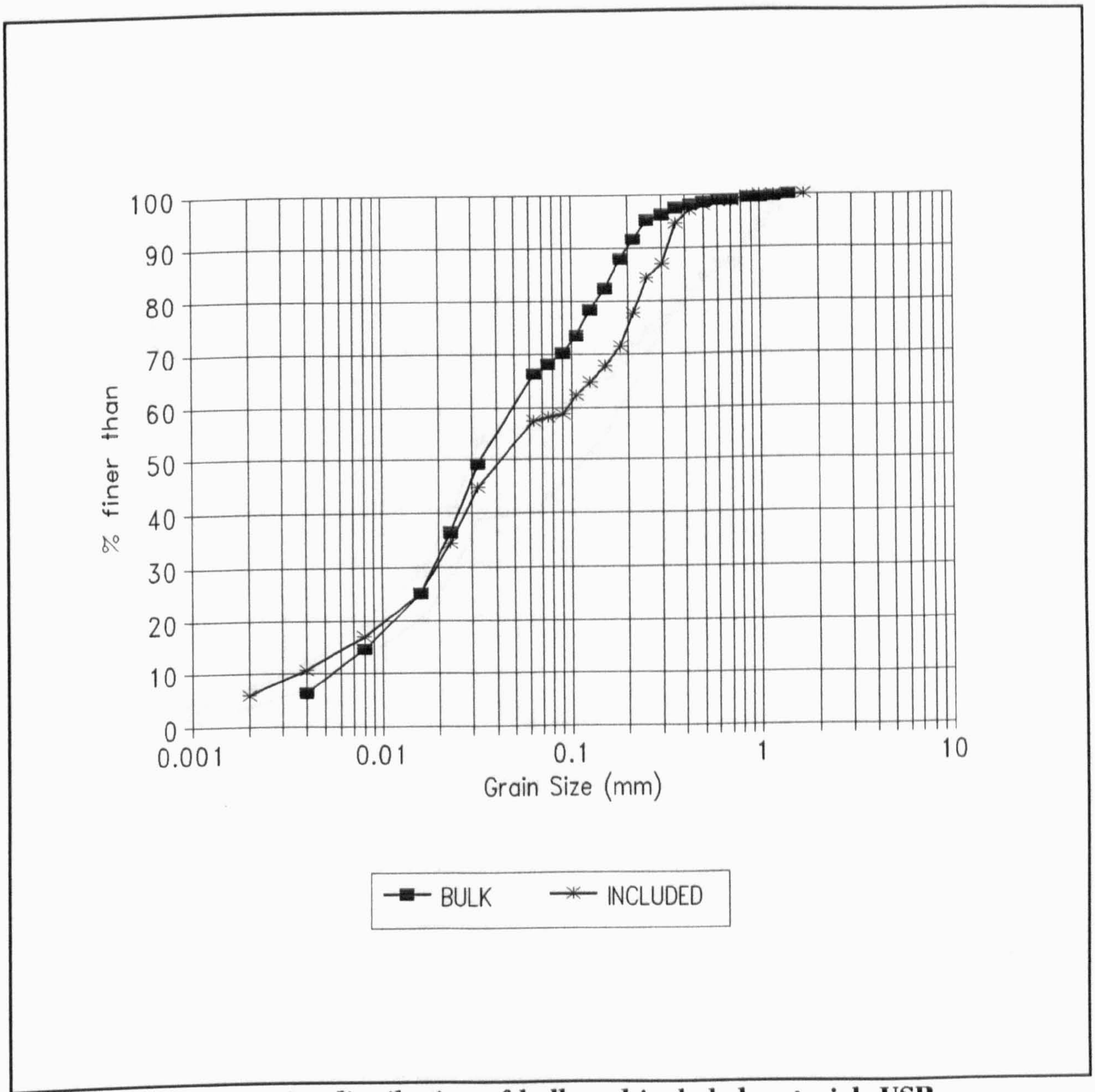

Figure 7.13 : Grain-size distribution of bulk and included material: USB$_1$

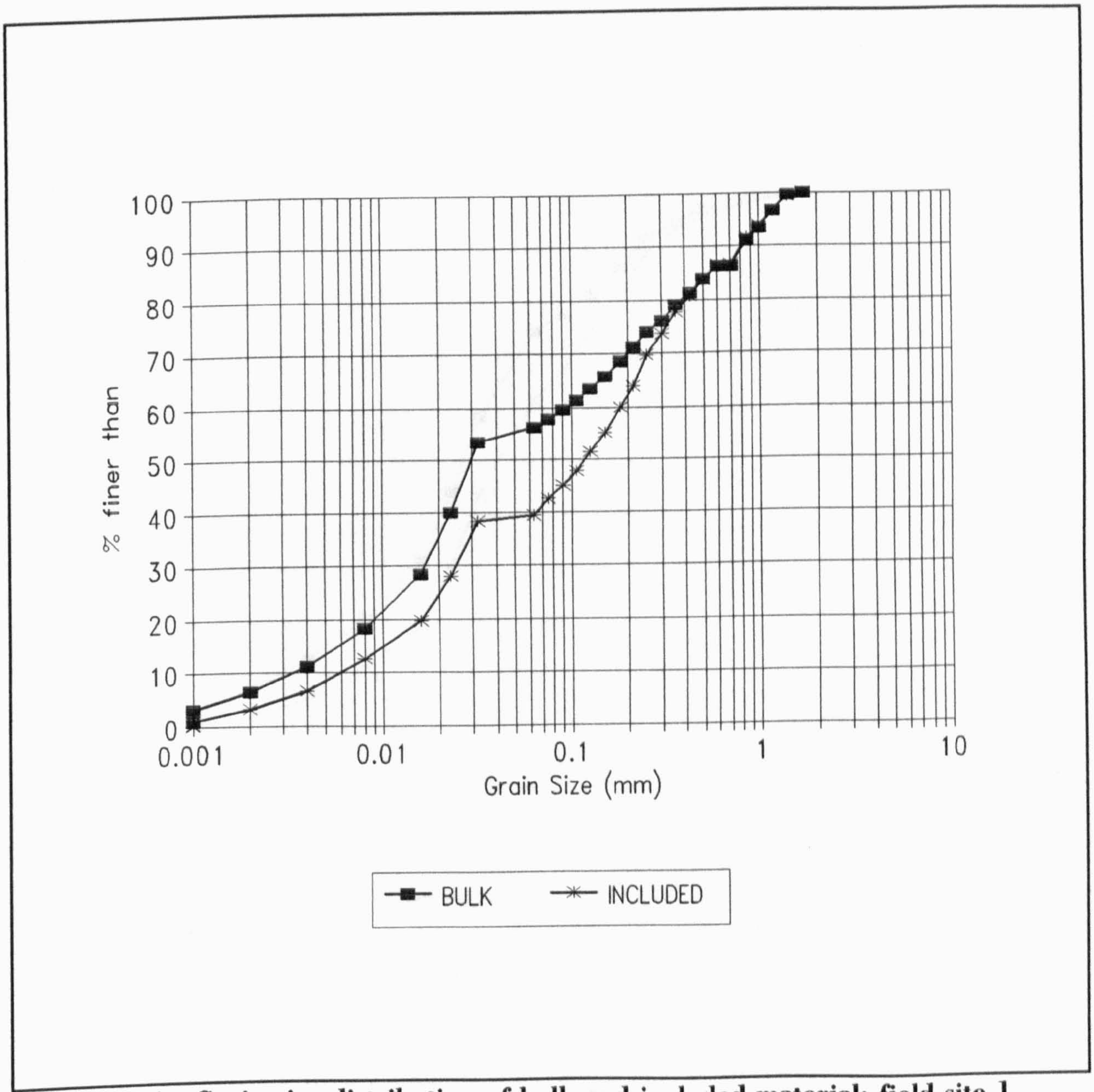

Figure 7.14 : Grain-size distribution of bulk and included material: field site 1

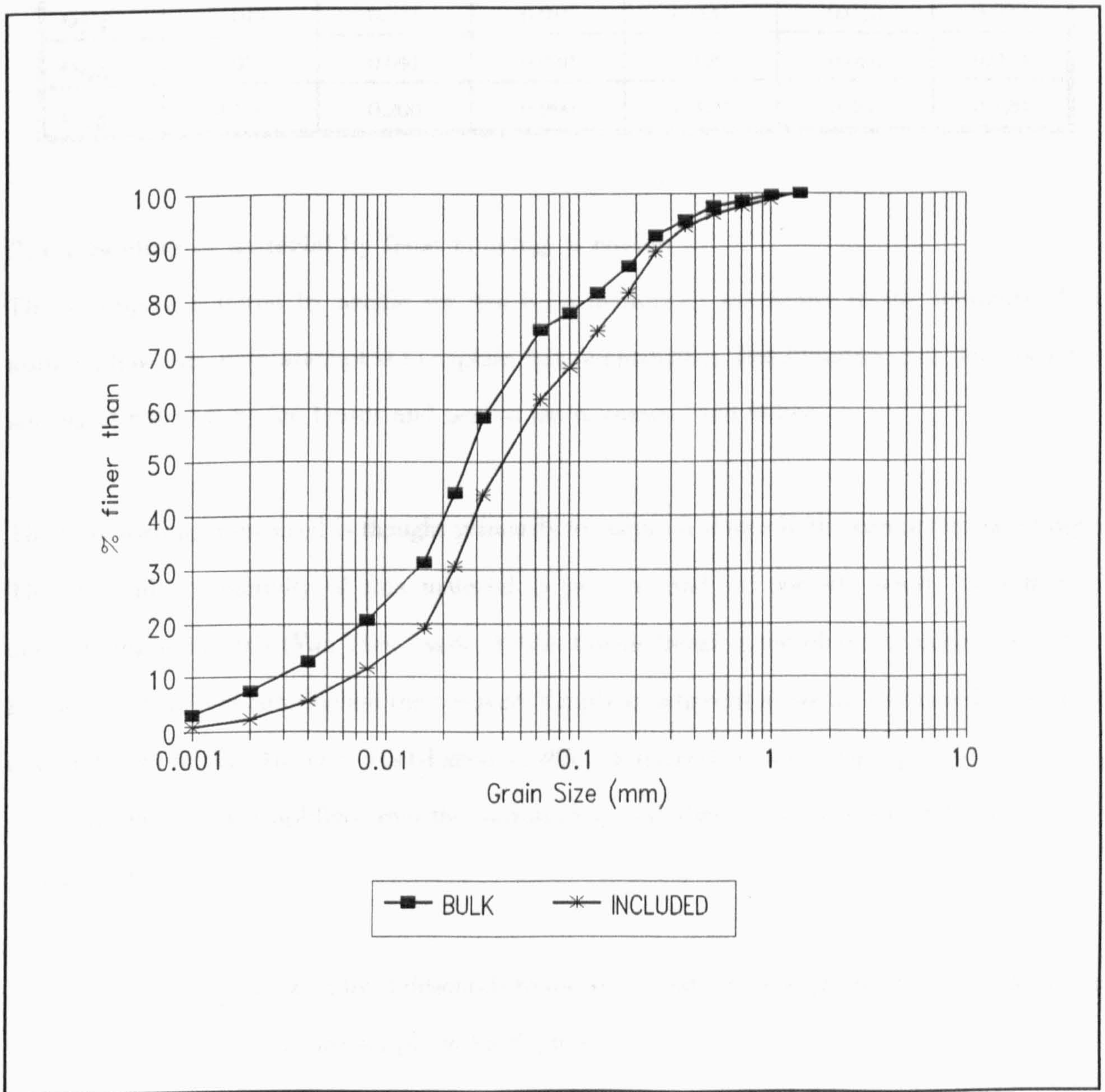

Figure 7.15 : Grain-size distribution of bulk and included material: field site 2

Table 7.2 : Summary of the grain-size composition of host and included material

Index	Grain size (mm)					
	USB_1		Field 1		Field 2	
	Bulk	Included	Bulk	Included	Bulk	Included
D_{25}	0.017	0.017	0.012	0.020	0.010	0.020
D_{50}	0.031	0.041	0.030	0.120	0.026	0.040
D_{75}	0.110	0.200	0.290	0.310	0.065	0.120

7.4.1 Sorting of material by frost heaving; a review

The sorting of material by needle ice has been mentioned frequently in the literature. Few authors, however, have attempted to explain this phenomenon. The literature that discusses the sorting of material by ice lenses and needle ice is summarised below.

The frost sorting of material is thought primarily to occur on stones in the centimetre size range. The thermal conductivity of this material is greater, and its porosity lower, than that of surrounding soil matrix (Van Vliet-Lanöe, 1985). During freezing, therefore, ice nucleates earlier below the stone and can deplete the moisture supply in adjacent areas (as discussed in Section 6.4 and Section 7.3.4). Van Vliet-Lanöe (1985), described a three-stage process by which material may become uplifted from the surrounding soil (based on the work of Kaplar, 1965) (Figure 7.16):

i) the freezing front descends to the stone and a pore appears above it and causes the moisture supply to be depleted in this area;

ii) the stone is raised as the soil matrix freezes and a small pore forms at the base of the stone;

iii) segregated ice forms in the hole below the stone and pushes the stone up.

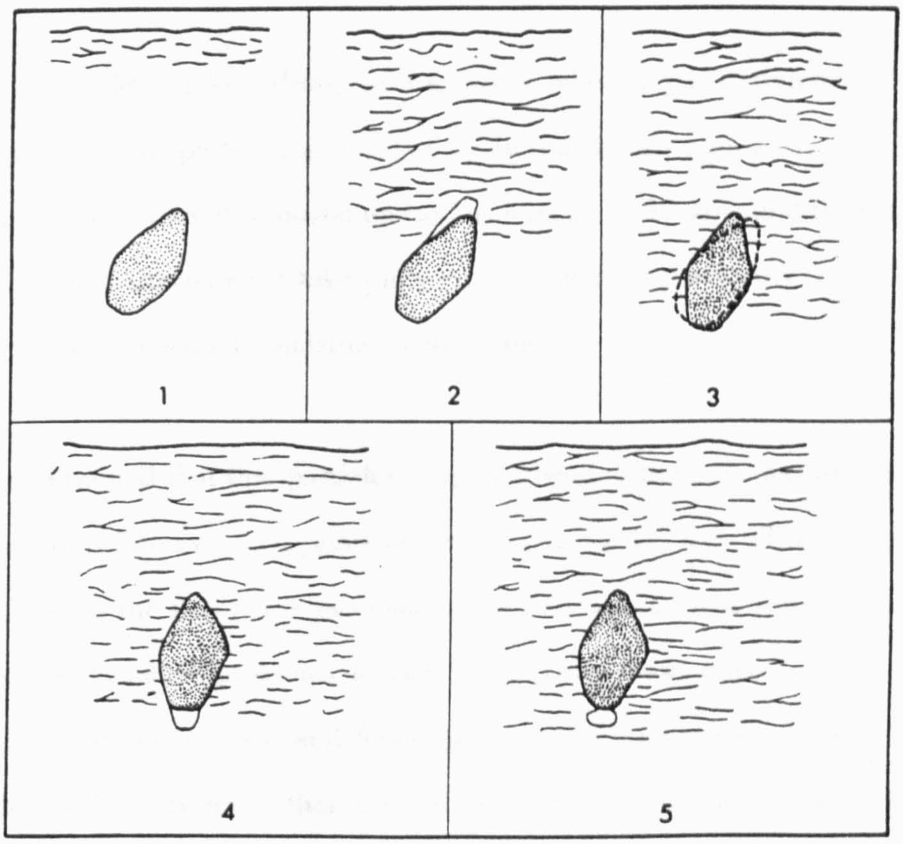

FIG. 5.17. ERECTION OF STONES BY DOWNWARD FREEZING OF SOIL, INVOLVING BOTH FROST 'PULL' AND FROST 'PUSH'. Growth of segregated ice *schlieren* produces void above stone (2). Stone moves into that space aided by frost 'pull' arising from ice adhesion (3). Void is left behind below stone (4). This becomes confined if deeper penetration of segregated ice occurs (5).

Figure 7.16 : The stone lifting process involving frost pull and frost push

(Source : Derbyshire *et al.*, 1979; p.212)

Washburn (1979) suggested that the upfreezing of stones can occur by either one of two processes; either 'frost push' or 'frost pull'. The former process is similar to that described by Van Vliet-Lanöe - ice forms beneath the coarser material and forces it up. During 'frost pull' ice initially develops close to the stones in material that contains fines. (This is a result of the greater thermal diffusivity of the stones than fines; the fines adjacent to the stone freeze earlier than fines away from stones.)

Corte (1961, 1962, 1963, 1965, 1966), in a series of laboratory experiments, also determined that coarser particles are preferentially lifted up by the freezing process. Corte (1961; p.20) stated that 'the fact that particles moved upward as a result of freezing and thawing from the top indicates that vertical sorting must take place in heterogenous seasonally frozen soil outside of the permafrost areas if adequate moisture is available'.

Corte (1961) determined that fine particles migrate ahead of the freezing line, whereas coarser particles are trapped into the ice crystals and remain in the ice lens. (The limited thickness of the adsorbed layer of the fine particles ensures that they are not frozen into the ice lens.) This process is thought to cause problems to farmers in some areas during severe winters where stones appear at the soil surface and fence posts are heaved out of the soil (Corte, 1961). Similarly, Jahn (1985) observed that wooden pegs moved up towards the soil surface. He suggested this indicates that the upfreezing of coarse materials in the soil is one of the most dynamic periglacial processes.

A study by Pérez (1991; p.250) discussed the sorting of coarse material by needle ice. He concluded that 'the pronounced lateral sorting of the coarse rod fractions is believed to result primarily from recurrent needle-ice growth'. In this case the needle ice lifted pebbles which were on or near the soil surface. When the crystals melted, the particles migrated into vehicle tracks and other surface indentations by creep and rolling.

7.4.2 Possible explanation of sorting in the present study

With regard to the sorting of fine material in this study, which occurred in particles less than approx 0.4 mm diameter, a similar process to that discussed by Corte (1961), and described above, is thought to occur. The process is related to the migration of the freezing front into the soil profile and is shown schematically in Figure 7.17. When needle-ice growth ceases, in-situ freezing occurs and thus the freezing front moves from the soil surface into the soil profile (Section 7.3.1 and Figure 7.17). As the freezing front descends, coarse particles may be frozen within the in-situ frozen layer (Figure 7.17B). The fine particles, however, have a very thin adsorbed layer of water around them, which may possibly remain unfrozen; these fines may then be 'pushed' ahead of the migrating freezing front. Once ice segregation recommences the in-situ frozen (coarse) material is incorporated between the two layers of needle ice (Section 7.3.1, Figure 7.17C).

This process may occur during the formation of monocyclic multitiered crystals, dirty crystals and frozen soil caps as it involves the descent of the freezing front, albeit at different spatial and temporal scales. When unfrozen soil caps are produced, however, the freezing front is established within the soil profile, ice segregation commences immediately and thus the freezing front remains stationary. Thus the material lifted in an unfrozen soil cap will probably have a similar grain-size distribution to that of the host soil, and should be investigated in future studies.

This study has only analysed sediment less than 2 mm diameter (Section 5.4.2) and differences in grain-size composition between the host and included material were only evident at grain sizes less than approx 0.4 mm. This suggests that the geomorphic implications of the process in this case are not likely to be very evident. Nevertheless, a concentration of coarser particles at the soil surface may affect the future frost susceptibility of the soil. Areas which are more susceptible to needle-ice growth may therefore be reinforced, although this will depend on the initial soil texture relative to the optimum. If needle ice is to be regarded as an agent which has a role in the formation of macroscopic sorting, however, then it is important that the analysis is

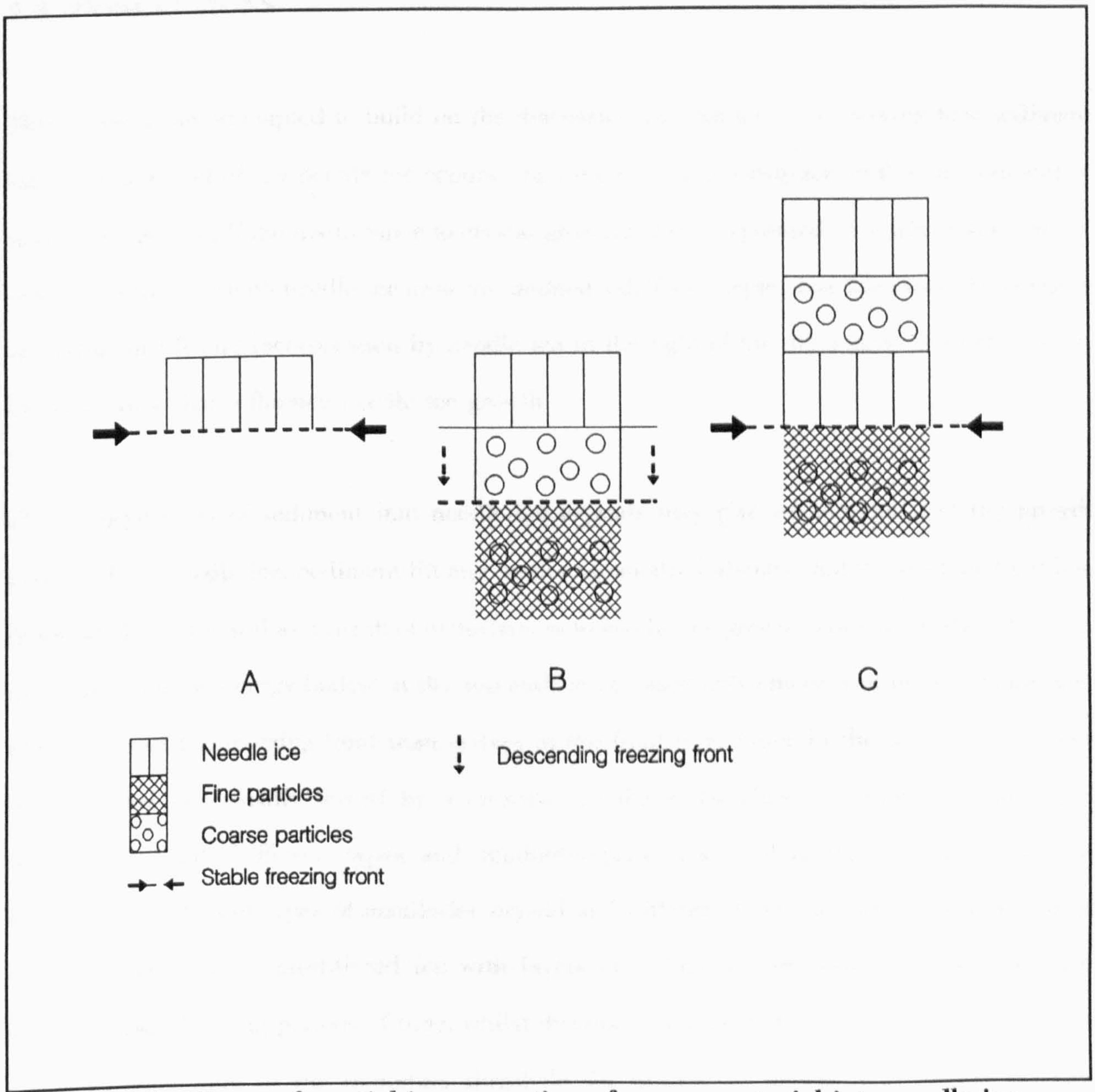

Figure 7.17 : The preferential incorporation of coarse material into needle ice

extended to include coarser particles, and shows that there is a difference in the particle-size distribution of the bulk and included samples.

7.5 CONCLUSIONS

This chapter has attempted to build on the discussion in Chapter 6 by showing how sediment incorporation and lift by needle ice occurs when there is an interruption to the environment of needle-ice growth. If the disturbance to crystal growth is to be explained, it is important that the conditions under which needle ice grow are understood. This chapter has discussed the controls on sediment lift and incorporation by needle ice in the light of the discussion in Chapter 6 on the processes that influence needle-ice growth.

The incorporation of sediment into needle-ice crystals may give an indication of the growth history of the needle ice. Sediment lift and inclusion usually indicates that the freezing front has descended into the soil as a result of disturbances to needle-ice growth. These disturbances seem to occur when the energy budget at the soil surface becomes unbalanced and there is more heat removed from the freezing front than arrives at the front from lower in the soil profile. These interruptions are usually forced by a decrease in the soil-surface temperature and/or soil-moisture content. Different types and spatial/temporal scales of disturbance result in the formation of different types of needle-ice crystal and different forms and amounts of sediment inclusion. Monocyclic multitiered ice with layers of sediment were formed when needle-ice growth ceased for long periods of time, whilst dispersed sediment incorporation occurred when the conditions were at the minimum threshold for needle-ice growth, and growth stopped frequently for short periods. The lift of sediment as caps and aggregates was influenced by the moisture conditions prior to freezing (this is discussed further in Section 9.3). Sediment caps were uplifted when soil-moisture content at the soil surface was below the critical threshold for growth. Ice segregation thus commenced within the soil profile where there was sufficient moisture. Aggregates of sediment were uplifted between crystals that grew discontinuously on the soil surface, due to heterogeneous soil characteristics.

An important conclusion from this chapter is that sediment can be incorporated into needle-ice crystals even when the external microclimatic conditions are constant. This is because the flow of soil moisture within the soil profile is often discontinuous over time. Conversely, if the soil-surface temperature decreases then there may be no soil incorporation if the flow of soil moisture increases and allows the equilibrium energy budget to be maintained. Moisture content thus seems to be the main factor that influences sediment incorporation.

A problem with the data from this type of study is that it is not possible to determine conclusively what type of needle ice was formed. In many cases visual examination of the needles is still the only way to distinguish between needle types. This is problematic because in order to predict the amount of sediment which will be associated with a given freezing event it is necessary to know the type of needle involved (see Section 9.3.3). It may be possible to distinguish between events that produced clear ice and ice with dispersed sediment, given knowledge of conditions prior to freezing and predicted temperatures (Section 9.3.3a). Clear needle ice is usually produced at high moisture contents and temperatures just below the ice nucleation temperature, whereas ice with dispersed sediment is produced with lower moisture contents and temperatures. However, given that the formation of monocyclic multitiered ice is controlled by the occurrence of variable factors (e.g. pulses of moisture flux, fluctuations in wind velocity) it is much harder to predict their growth.

The material included within the needle ice was coarser than the soil from which it was lifted. It is as yet uncertain whether the nature of, and process controlling, the preferential inclusion of coarser particles observed in this study, is related to the processes which form patterned ground. Nevertheless, preferential uplift may cause small scale variations in grain-size distribution through the soil profile, with coarser particles at the top of the profile. Preferential incorporation was thought to occur in this study by fine particles being pushed in front of a migrating freezing front, unlike the coarse particles which are incorporated into the ice.

The disaggregation of the soil by lift and/or incorporation by needle ice is an important stage in the process of soil erosion in many parts of the world. When the needle-ice crystals melt the disaggregated sediment is deposited onto the soil surface. The following chapter discusses the processes of needle-ice melt and sediment transport which occurs as a result of melt.

Chapter 8

NEEDLE-ICE MELT AND THE TRANSPORT OF SEDIMENT BY NEEDLE ICE

8.1 INTRODUCTION

When needle-ice crystals melt, the lifted/incorporated sediment (Chapter 7) is deposited onto the soil surface. When this occurs on a slope the material is often deposited downslope of the position from which it was lifted (Section 3.3). In this chapter the patterns and mechanisms of needle-ice melt and sediment transport by needle ice are described with reference to data from the laboratory study. Analysis and modelling of the data discussed in this chapter are presented in Section 9.4.

Sediment was transported in both downslope (d) and horizontal (a) directions (the latter occurs when the sediment moves across the slope; sometimes termed 'lateral transport') - see Figures 8.1 and 8.2. Negative downslope values indicate that the marker has moved upslope (denoted by d_u). Negative horizontal movement indicates that the marker has moved to the left of the sample box (looking uphill) (a_l) and positive to the right of the box (a_r) (Figures 8.1 and 8.2).

Details of the soil sample, slope angle and marker particles used in the individual experiments discussed in this chapter are given in the figure captions. Where regression relationships are significant at the 95% confidence level the regression line has been drawn on the figure. Summary data for all transport experiments are presented in Appendix 5.

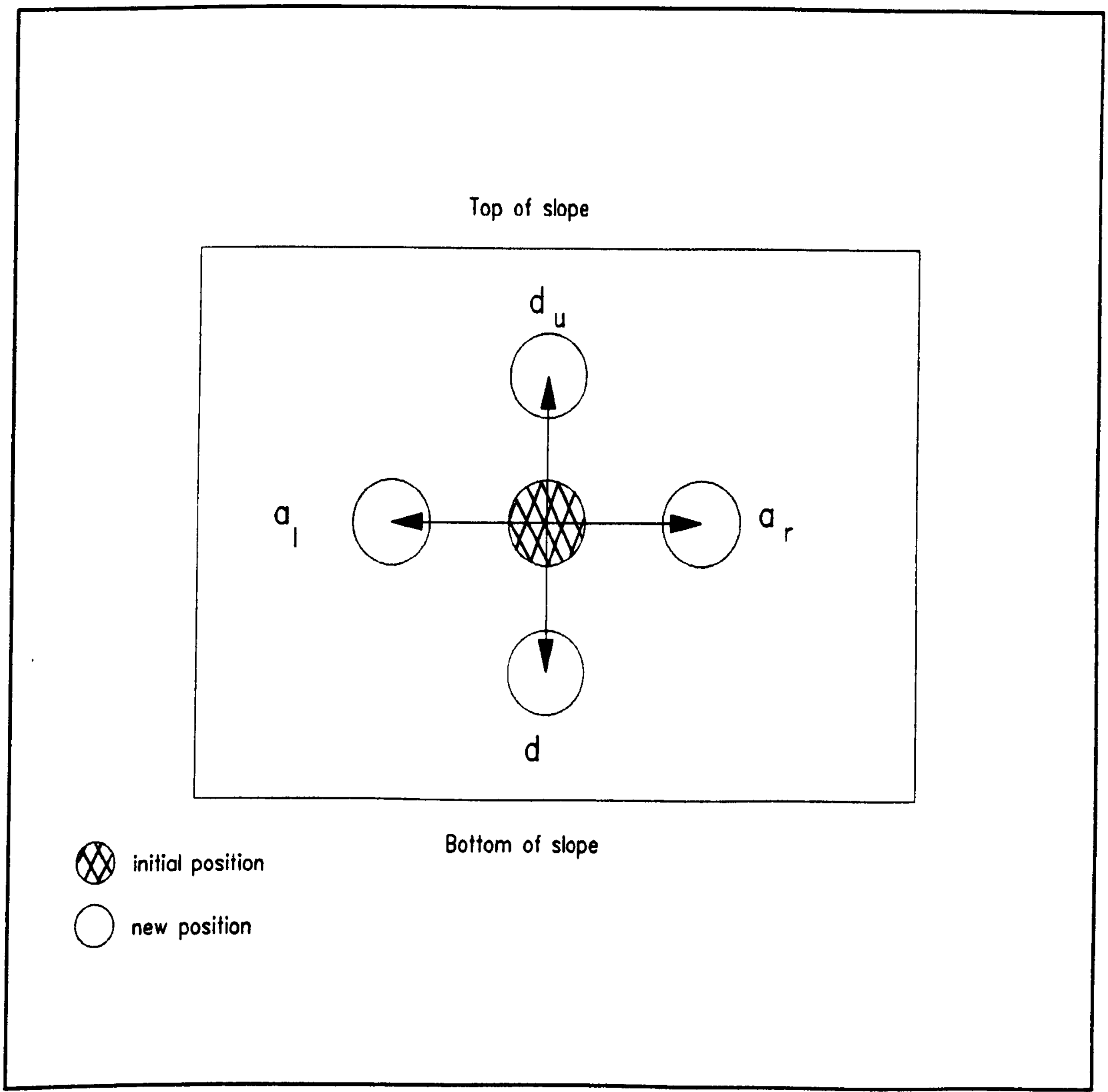

Figure 8.1 : Directions of sediment movement

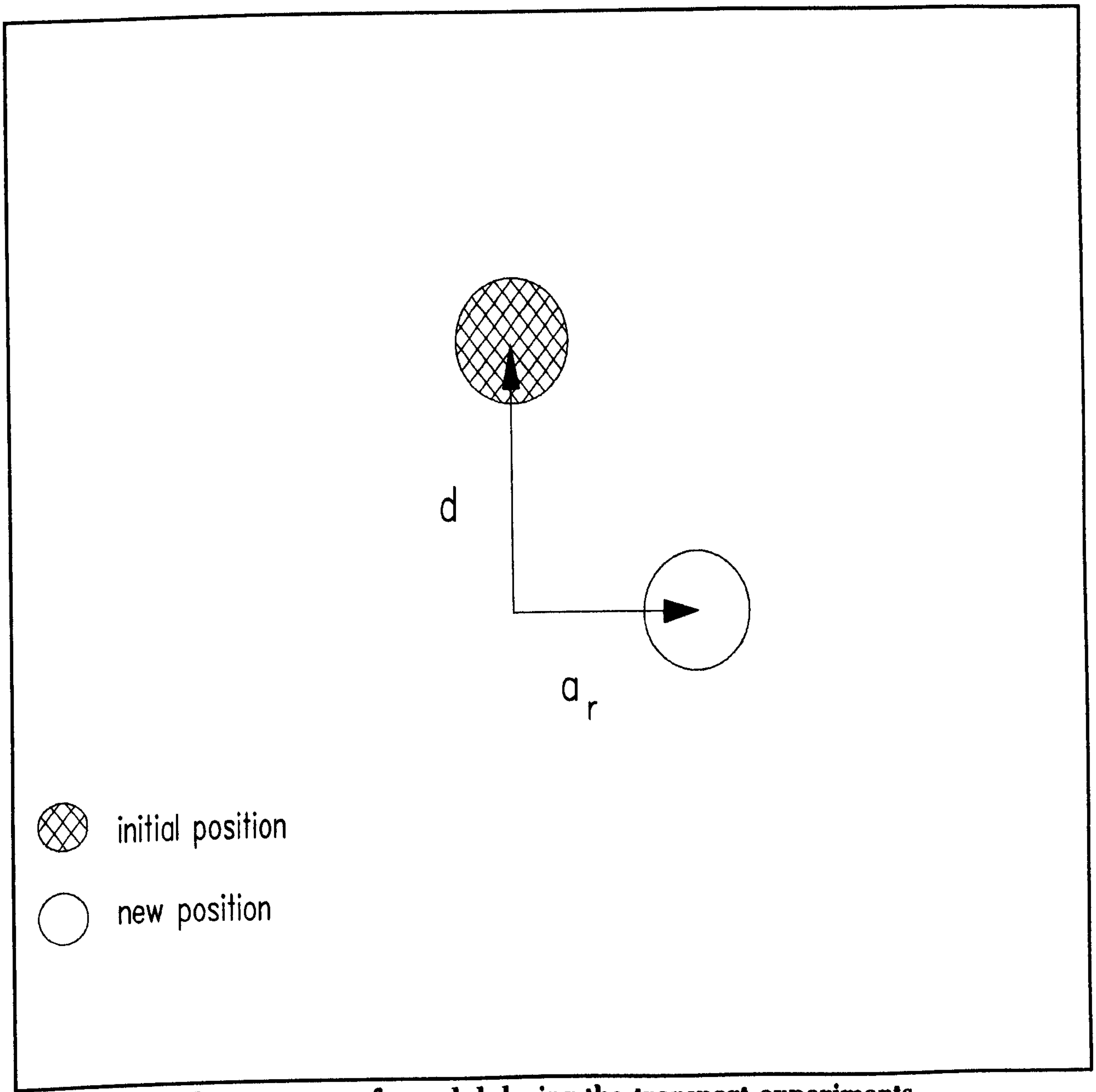

Figure 8.2 : Measurement of a and d during the transport experiments

To avoid equations that predict the movement of sediment when there is no needle ice, wherever possible, the y-intercept of regression relationships has been forced through zero. (It should be noted that sediment movement can occur as a result of frost heave effects when there is no needle ice (e.g. Young, 1960; Matsuoka *et al.*, 1988), but the purpose of the analysis in this chapter is to determine the influence of needle-ice growth only on sediment transport.) A possible problem with this method is that the fitted line may not minimise the 'y' residuals and the standard error of the predictions may be higher than from an equation which includes a constant. When the equations with and without a constant in this study were compared, however, there was only a small difference between the standard errors and the R^2 value of the predictions, and the difference in the standard error of the equations was less than the error of the measurement technique. Two typical examples are given in Table 8.1.

Table 8.1 : Comparison between regression equations with and without a constant

DSB_1, stones

Slope angle (°)	Equation	R^2 (%)	St.error d-est. (mm)	no. of markers
5	$d = -0.46 + 0.51\ h$	24	3.37	54
	$d = 0.44\ h$	24	3.25	54
22	$d = -1.41 + 0.85\ h$	68	3.51	44
	$d = 0.73\ h$	66	3.58	44

all significant at 95% confidence level

8.2 NEEDLE-ICE MELT

8.2.1 Patterns of needle-ice melt

Figures 8.3, 8.4 and 8.5 show typical profiles of needle-ice melt. These are divided into three types: toppling (Figure 8.3), gradual melt (Figure 8.4) and a combination of fracture and melt

(Figure 8.5); they are shown schematically in Figure 8.6. Which of these processes occurred at any one time was dependent on the type and spatial cover of crystals that melted. Similar processes have also been reported by Fukuda (1936), Gerlach (1959) and Ellenberg (1974).

8.2.1a Toppling. Toppling was common when needles grew either in dispersed clusters or individually on the soil surface. It is assumed that the crystals started to melt at the base and toppled over (Figures 8.3 and 8.6A). The toppling event is marked by a rapid decrease in the height of the crystals: in the case of Figure 8.3 this occurs just over two hours after melting commenced. After the needles toppled they melted gradually in their new position, and there was a further slow decrease in the height of the crystals.

8.2.1b Gradual melt. Crystals were observed to melt gradually from above when there were larger bunches of crystals bound together, and thus it appears that external heat could not penetrate to the base of the crystal. The crystal thus melted from the top (Figures 8.4 and 8.6B). Fukuda (1936) thought that this was the most common type of melt, although in the present study its occurrence was dependent on the density of needle-ice growth (Section 8.2.4).

8.2.1c Combination of fracture and gradual melt. Some crystals underwent a combination of fracture and gradual melt (Figure 8.5). The top of the crystal broke off and melted gradually; the part of the crystal that was still upright then either melted gradually (as in Figure 8.6C) or toppled. This process was common when the crystals were over c.20 mm long.

Gerlach (1959) noted that at the beginning of an ablation sequence, compact layers of needles tended to melt from the top of the crystal. Later, as solar radiation penetrated to the soil surface, he observed that the needles melted at the base and toppled over. This process was not observed in the laboratory experiments when the needles were left to melt without direct heating;

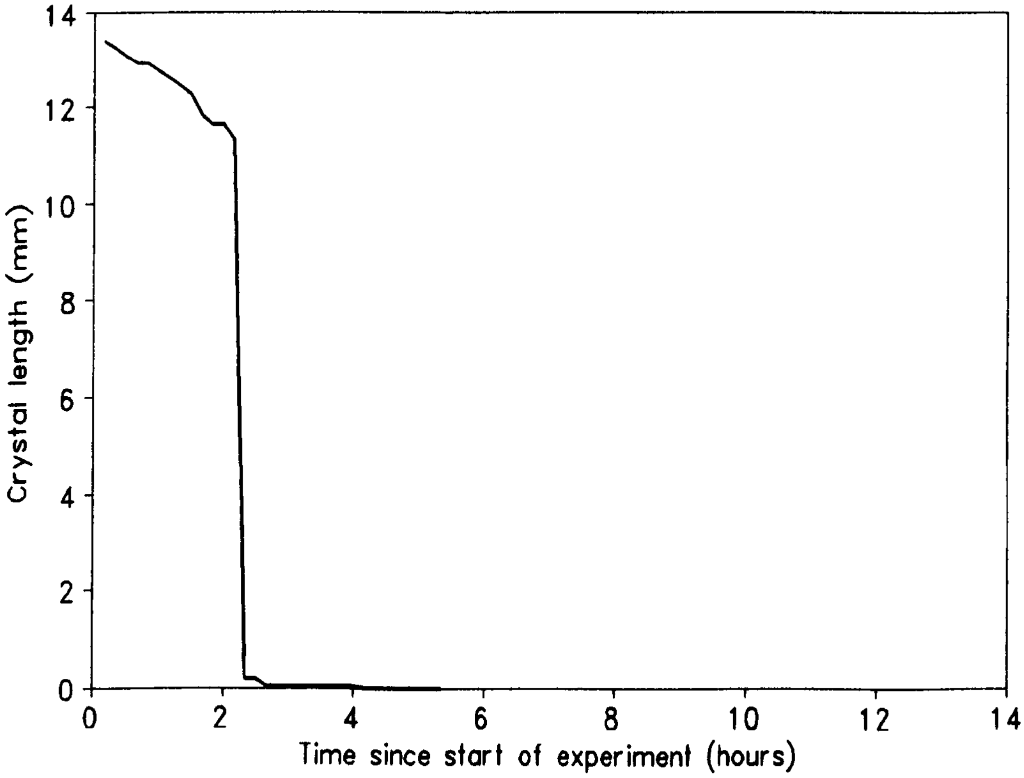

Figure 8.3 : Experiment 21/3/92; typical profile of needle-ice melt - toppling

USB_2, 15°

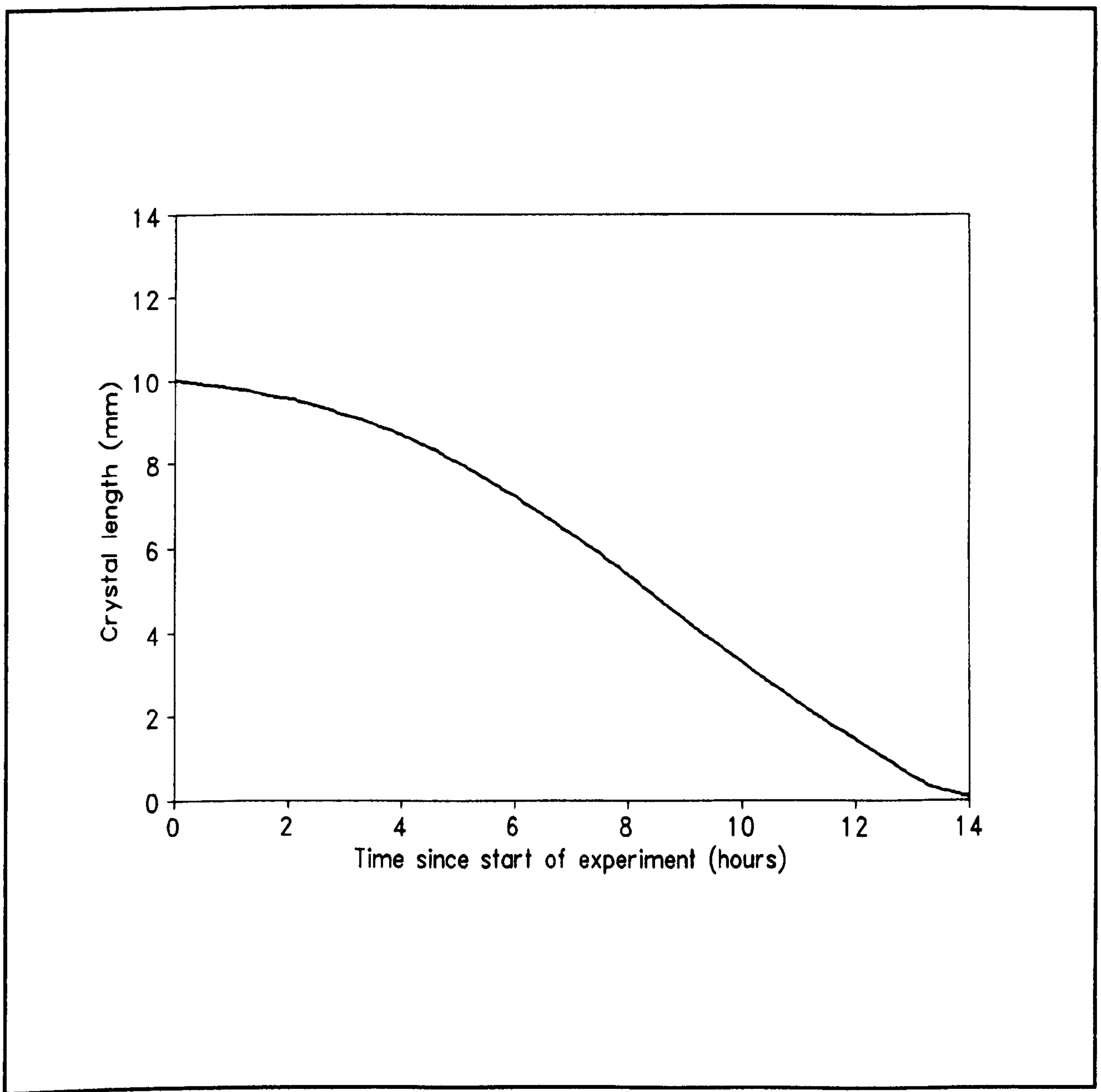

Figure 8.4 : Experiment 25/11/91; typical profile of needle-ice melt - gradual melt
DSB_1, 15°

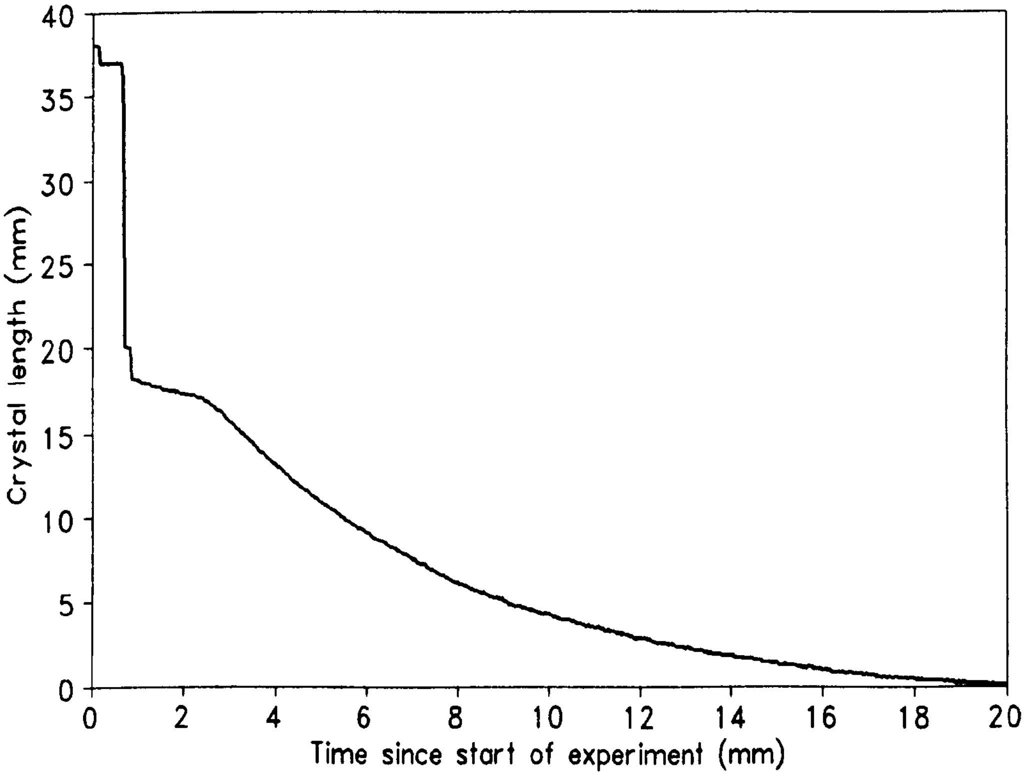

Figure 8.5 : Experiment 16/1/92; typical profile of crystal melt where the crystal toppled and then gradually melted USB_2, 15°

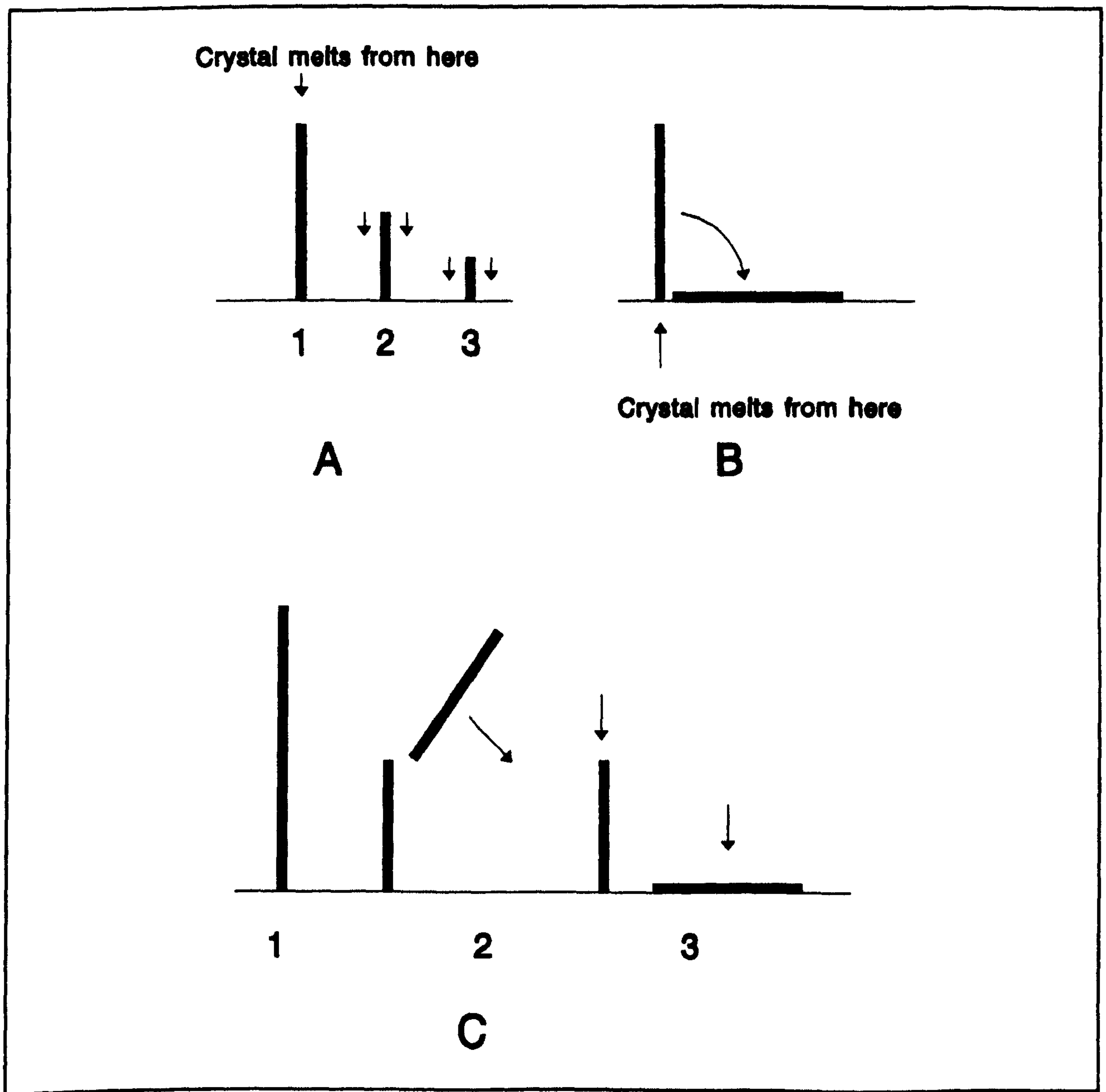

Figure 8.6 : Schematic representation of the processes of needle-ice melt (A: toppling; B: gradual melt; C: combination of fracture and melt)

presumably because there was little radiant heat. When the crystals were thawed with a heat lamp, however, this melt/topple process was observed.

8.2.2 The release of moisture during needle-ice melt

As expected, when the needle-ice crystals melted, the meltwater was released onto the soil surface. This percolated into the soil profile and was not observed to run off the slope. Evidence of this is given by the analysis of moisture contents at the soil surface before (M_{sb}) and after (M_{sa}) crystal melt (Figure 8.7). The mean difference between M_{sb} and M_{sa} was 3.4 % (min = 1.0 %; max = 8.0 %; st. dev. = 2.2 %; n = 15).

Data from the moisture elements also show this flux of water from the soil surface into the soil profile. Figure 8.8 presents data from an extreme example; the moisture content near the soil surface (M_1) began to increase about 45 minutes after melting commenced. After the crystals had melted completely the soil-moisture content was 7% higher than at the start of the experiment.

The amount of water released was influenced by the density of needle-ice cover on the soil surface. The amount and speed of moisture release was important because if there was too much water to infiltrate into the soil, then sediment was observed to move down the slope in rivulets of meltwater (Section 3.3.1c); although this was only observed when the needles melted very quickly (i.e. in the limited number of experiments when the soil was heated with a lamp; Section 8.2.3a).

8.2.3 The rate of needle-ice melt

The needle-ice crystals melted at rates between 0.6 mm h^{-1} and 32 mm h^{-1}. The melt rate seemed to be influenced by the energy balance at the top and bottom of the ice needles and the location and amount of sediment in the ice sample.

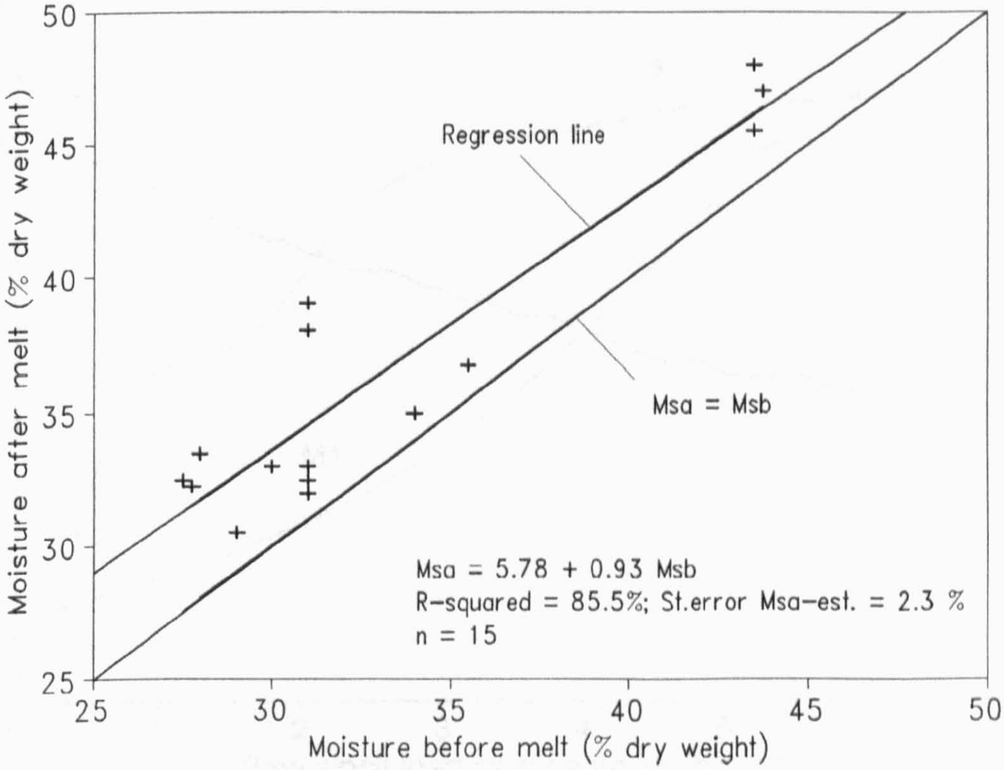

Figure 8.7 : Soil-moisture contents before (M_{sb}) and after needle-ice melt (M_{sa})

DSB_1 and USB_2

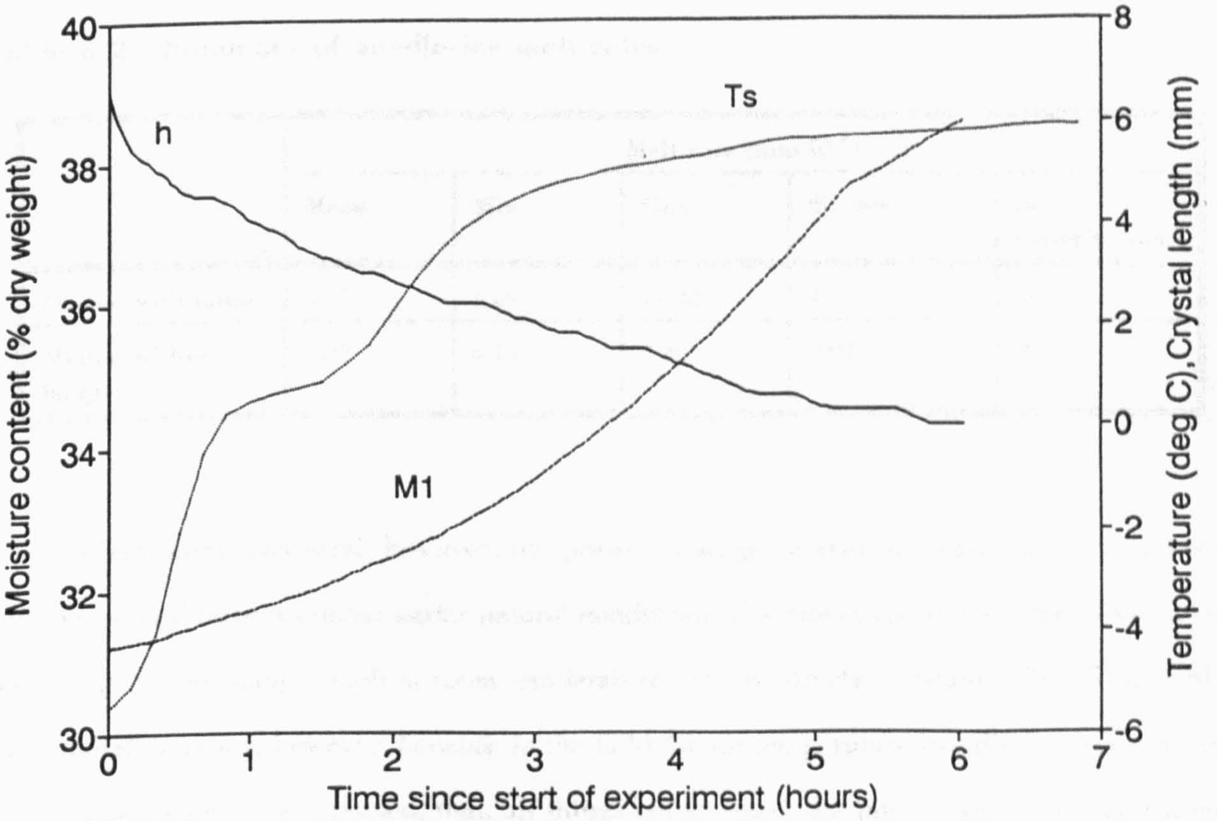

Figure 8.8 : Experiment 26/11/91; the release of moisture during needle-ice melt

USB$_2$

8.2.3a Energy balance at the soil surface. When the soil surface was heated with a heat lamp, as expected, the crystals melted considerably quicker than when no heat was applied. Figure 8.9 shows data from a representative experiment where a heat lamp was used. The crystal, which was 34 mm long melted completely in 1.75 h. Table 8.2 shows summary data of the rates at which needle-ice crystals ablated for experiments where the needles were left to melt at room temperature and for experiments where a heat lamp was used.

Table 8.2 : Summary of needle-ice melt rates

	Melt rate (mm h^{-1})				
	Mean	**Min**	**Max**	**St. dev**	**no. of experiments**
Melted with lamp	8.67	6.49	19.43	4.60	10
Melted without lamp	2.05	0.71	4.33	0.97	25

When a heat lamp was used, however, the positive energy balance increased at a much faster rate than would have occurred under natural conditions. For most experiments, therefore, it was decided to let the sample melt at room temperature (at a relatively constant 18°C). This is also an artificial situation, however, because in the field the air temperature usually increases during the morning. Thus, it is expected, that, all things being equal, the rate of needle-ice melt would increase during the thawing cycle. It is not known whether these rates of needle-ice melt are representative of what occurs under natural conditions, given a lack of relevant field data. However, even though the air temperature was relatively constant, it is expected that temperatures at the ice and soil surface will rise slowly (future experiments should aim to monitor temperatures at these locations) and this rise may simulate early-morning warming, although the temperatures probably did not increase as rapidly as in the field. It is not thought, however, that the differing rates would affect the actual <u>process</u> of melt, which is the primary interest of this study. In this

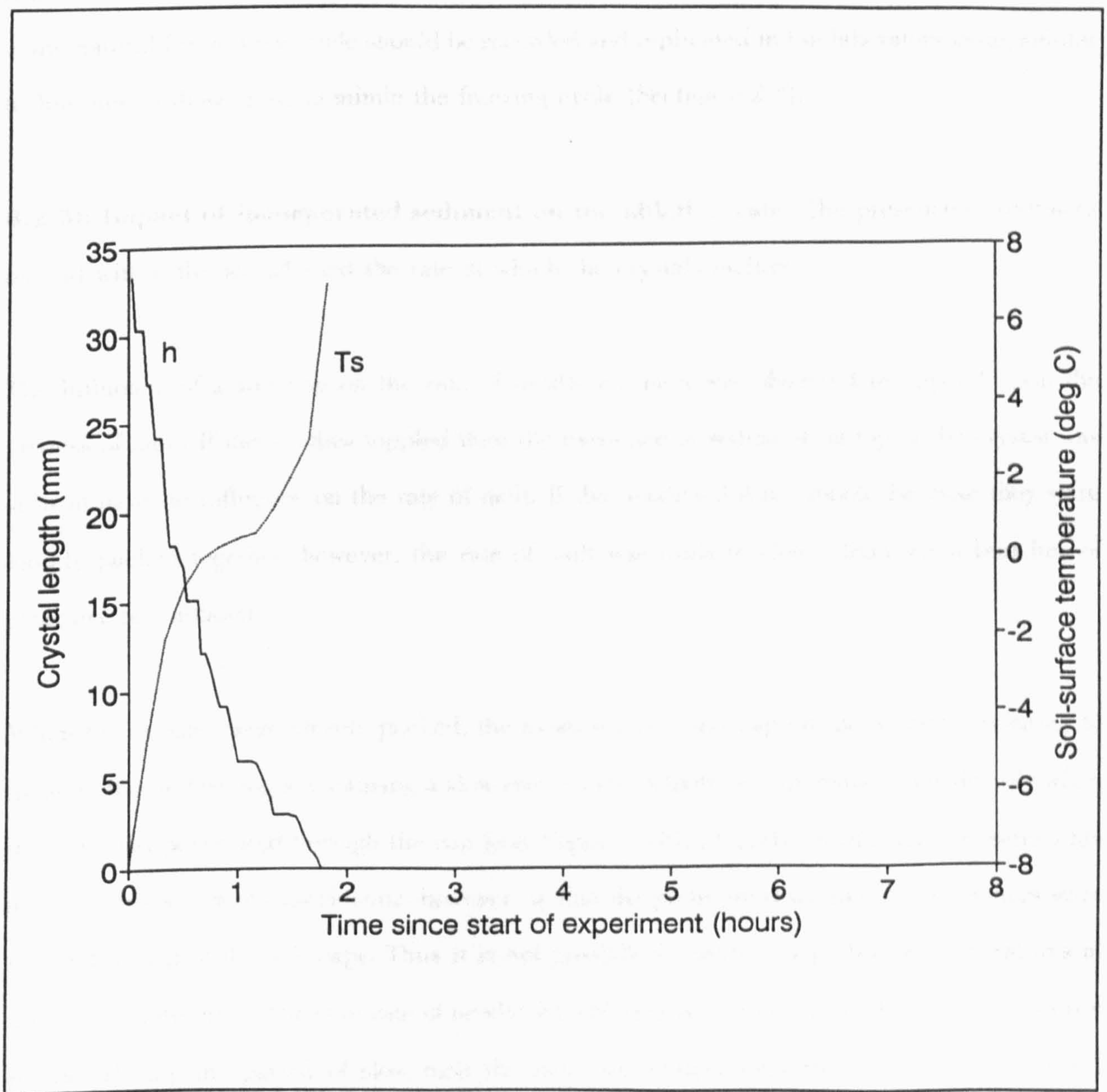

Figure 8.9 : Experiment 13/1/92; melt of crystal when a lamp was used to heat the soil surface USB_2

chapter, unless otherwise stated, the data are from needle ice that was melted at room temperature.

It is recommended that in future studies of needle ice, the temperature during the thaw section of the natural freeze-thaw cycle should be recorded and replicated in the laboratory using similar techniques to those used to mimic the freezing cycle (Section 5.2.3).

8.2.3b Impact of incorporated sediment on the ablation rate. The presence of sediment on and within the ice affected the rate at which the crystals melted.

The influence of a soil cap on the rate of needle-ice melt was observed to depend upon the process of melt. If the needles toppled then the existence of sediment on top of the crystal was seen to have no influence on the rate of melt. If the needles did not topple because they were closely packed together, however, the rate of melt was initially slower than when bunches of clear crystals ablated.

When the needles were closely packed, the existence of a soil cap on the needles appeared to insulate the underlying ice, causing a slow rate of melt, which then increased, presumably when the heat had penetrated through the cap (e.g. Figure 8.10). (A problem with the measurements made in this series of experiments, however, is that the platinum resistance thermometers were uplifted on top of the soil caps. Thus it is not possible to produce a profile of temperatures at the soil/ice interface.) The slow rate of needle-ice ablation is also evidenced by the soil-moisture profile. During the period of slow melt the moisture content near the soil surface remained relatively constant, the moisture content then started to increase when the rate of melt increased.

Crystals that contained dispersed sediment (Section 7.2.2) melted faster than clear crystals of the same height. A typical example of this is shown in Figure 8.11; the clear and dirty crystal

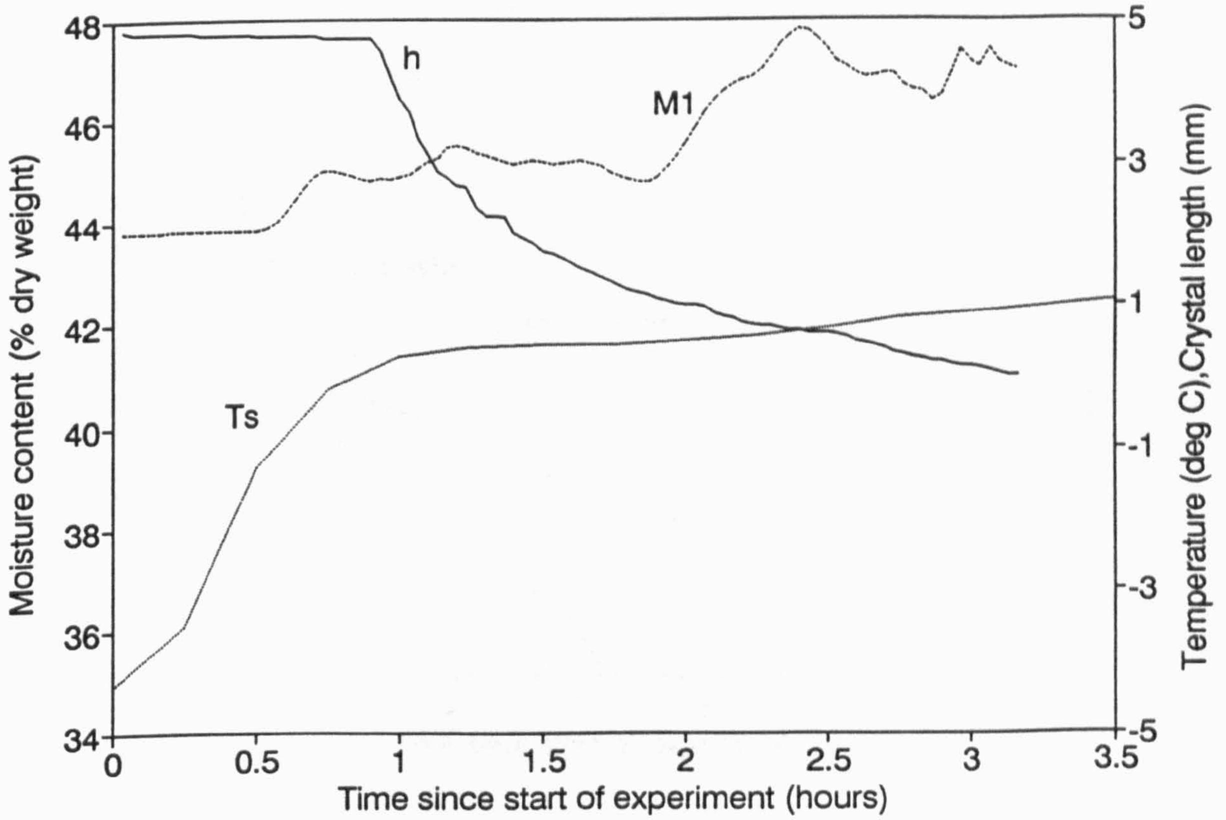

Figure 8.10 : Experiment 9/7/91; melt of a crystal with a soil cap

USB$_2$, 15°

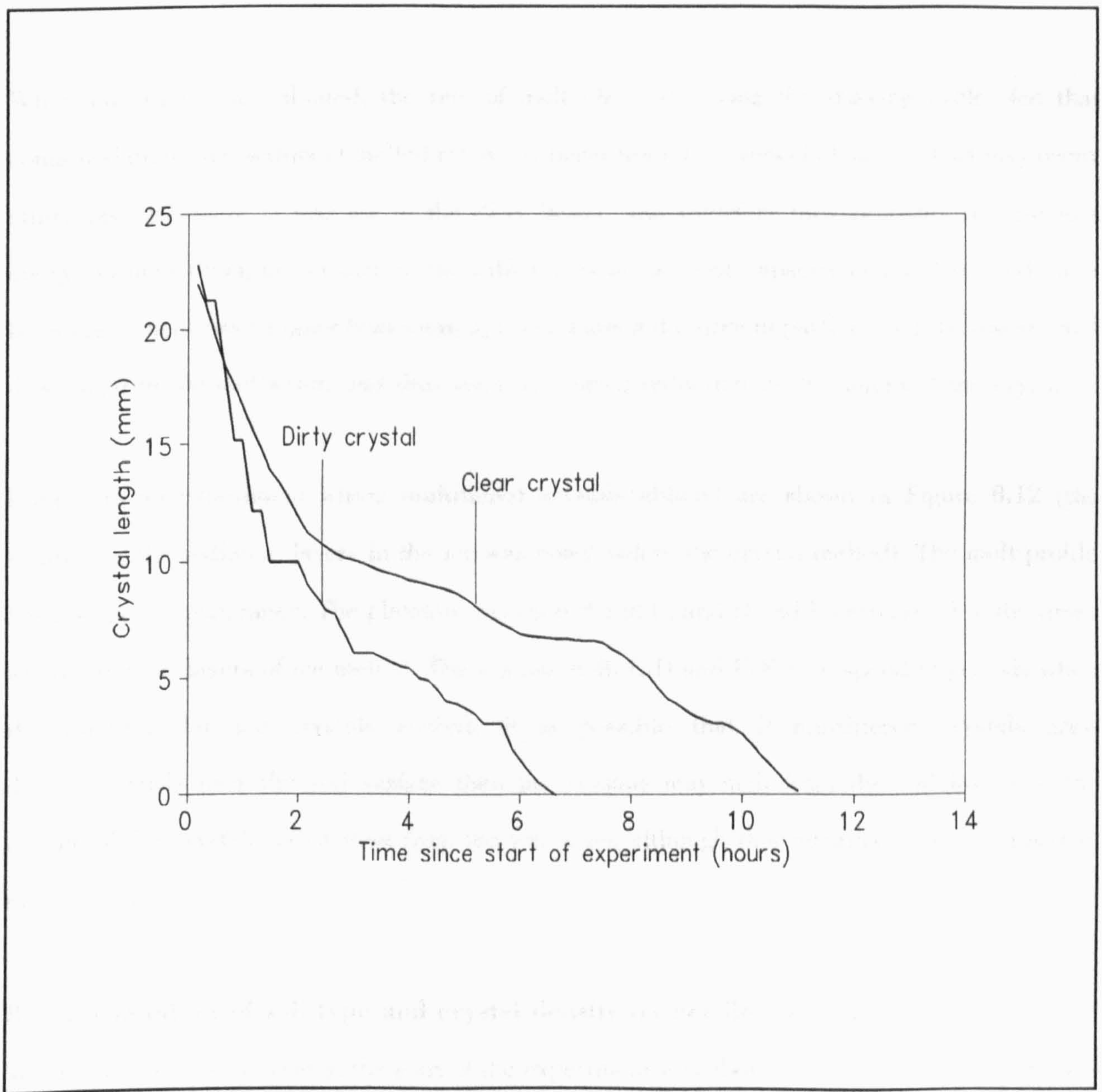

Figure 8.11 : Experiment 20/3/91; typical profiles of the melt of a clear and dirty crystal **USB_1, 15°**

were produced during the same experiment and thus experienced the same environmental conditions when melting occurred. The crystals ablated at different rates because the sediment has a higher thermal conductivity and heat capacity than ice, and the soil therefore absorbs heat which then melts the surrounding ice.

When multitiered ice ablated, the rate of melt changed during the thawing cycle. Ice that contained dispersed sediment melted relatively faster than the layers of clear ice. This may occur either because there is less ice in the dirty layers, and therefore they probably require less energy to melt them, or because of the differences in the heat capacity of the dirty and clear layers (sediment has a higher heat capacity). The loosened sediment particles will be transported downslope in the meltwater, and thus there is a rapid reduction in the height of the crystal.

Data from an experiment where multitiered crystals ablated are shown in Figure 8.12 (the location of the sediment layers in the ice was noted before the crystal melted). The melt profile has a stepped appearance. The plateaux, between B and C, and D and E correspond to the times when the clear layers of ice melted. The regions A-B, C-D and E-F correspond to periods when the intergranular ice crystals melted. It is possible that if multitiered crystals grew discontinuously over the soil surface then the crystals may melt from the soil layers in the middle of the crystal, rather than from the top down, although this remains to be examined in future work.

8.2.4 The effect of soil type and crystal density on needle-ice melt

When the moisture content at the start of the experiment was above 40% the needle-ice crystals usually grew closely packed together on the disturbed soil samples (Section 6.4), and crystals were observed to melt gradually from the top. When the moisture content of the disturbed samples was limited, however, the needles were often dispersed over the soil surface (Section 6.4). Thus, the heat could probably penetrate to the base of the needles more readily, and this

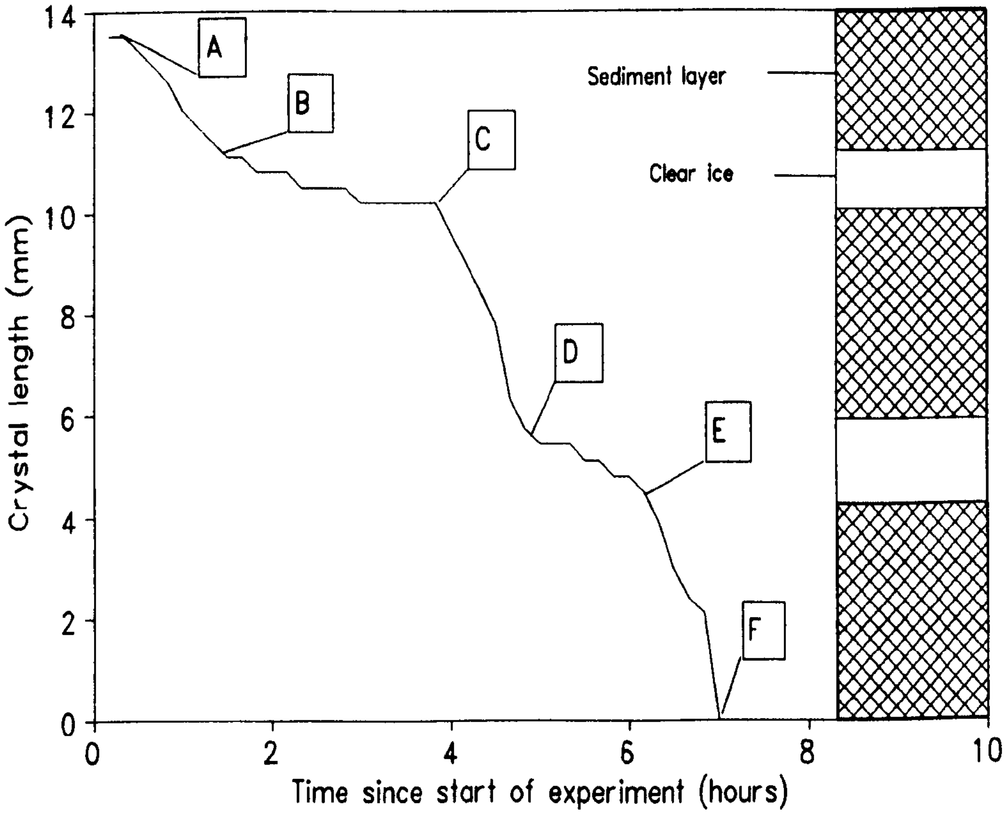

Figure 8.12 : Experiment 3/1/92; the melt of a multitiered ice crystal

USB_2, 15°

encouraged toppling. Regardless of the moisture content of the undisturbed samples the crystals were usually dispersed over the soil surface (Section 6.4), and thus most of the crystals toppled over.

Evidence that toppling was not common on the surface of DSB_1 is given in Figure 8.13; the line d = h indicates the distance that markers would be transported if the needles simply toppled (Section 3.3.1b). All but 5 of the 64 values are below the $d = h$ line. Figure 8.14, the movement by markers on USB_2, shows a greater amount of variation than Figure 8.13 and one third of the points are above the $d = h$ line.

8.3 FACTORS THAT AFFECT THE DISTANCE OF SEDIMENT TRANSPORT

In most other studies of sediment transport the distance that markers were transported has been related to the height of the needle-ice crystal and the tangent of slope angle (Section 3.3.1). No other factors have been taken into account. In the present study, however, the distance of marker transport was observed also to be influenced by the process of needle-ice melt (which was itself partly controlled by soil type) and type of marker. In the laboratory experiments an attempt was made to keep all of these factors, except one, constant in turn.

8.3.1 Needle-ice height and slope angle

Figure 8.15 shows the relationship between needle-ice height and distance of sediment transport on all slope angles for both soil types. As expected, the longer the needle-ice crystal, the further that the markers were transported. The plot is slightly curvilinear which indicates that the longer the crystal, is the more important it is in controlling the distance of marker transport. There is also an interesting cross-over at c. 25 mm crystal length where the distance of transport is greater than needle height. This implies that there is some onward movement of the marker after

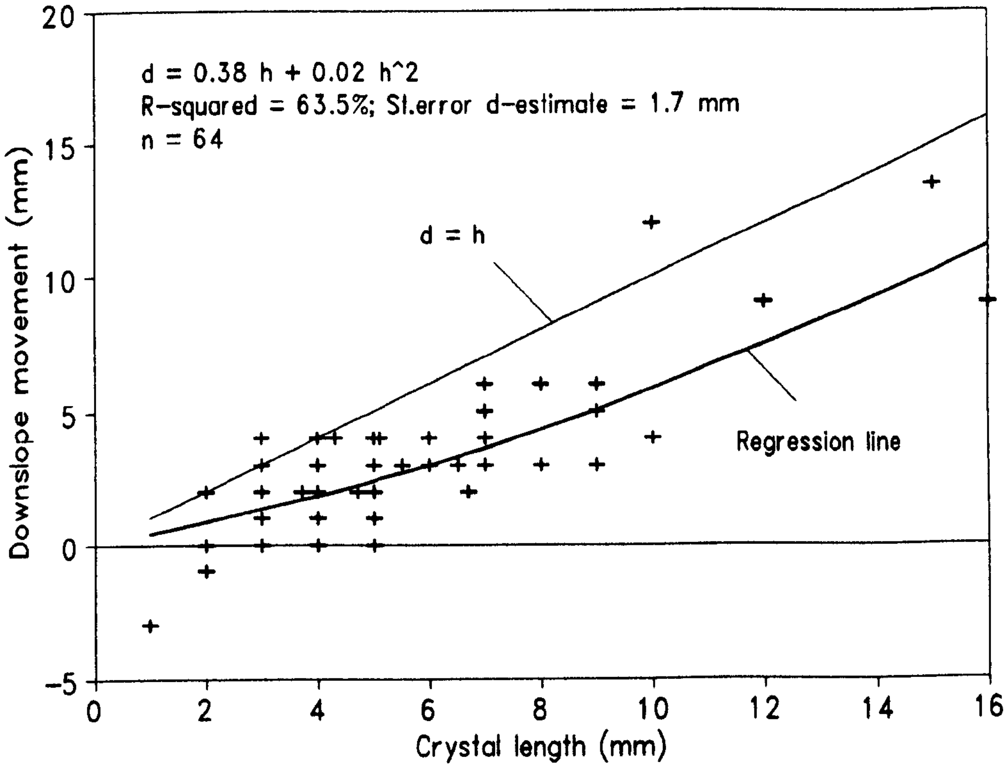

Figure 8.13 : Transport of particles on DSB$_1$ **15°, stones**

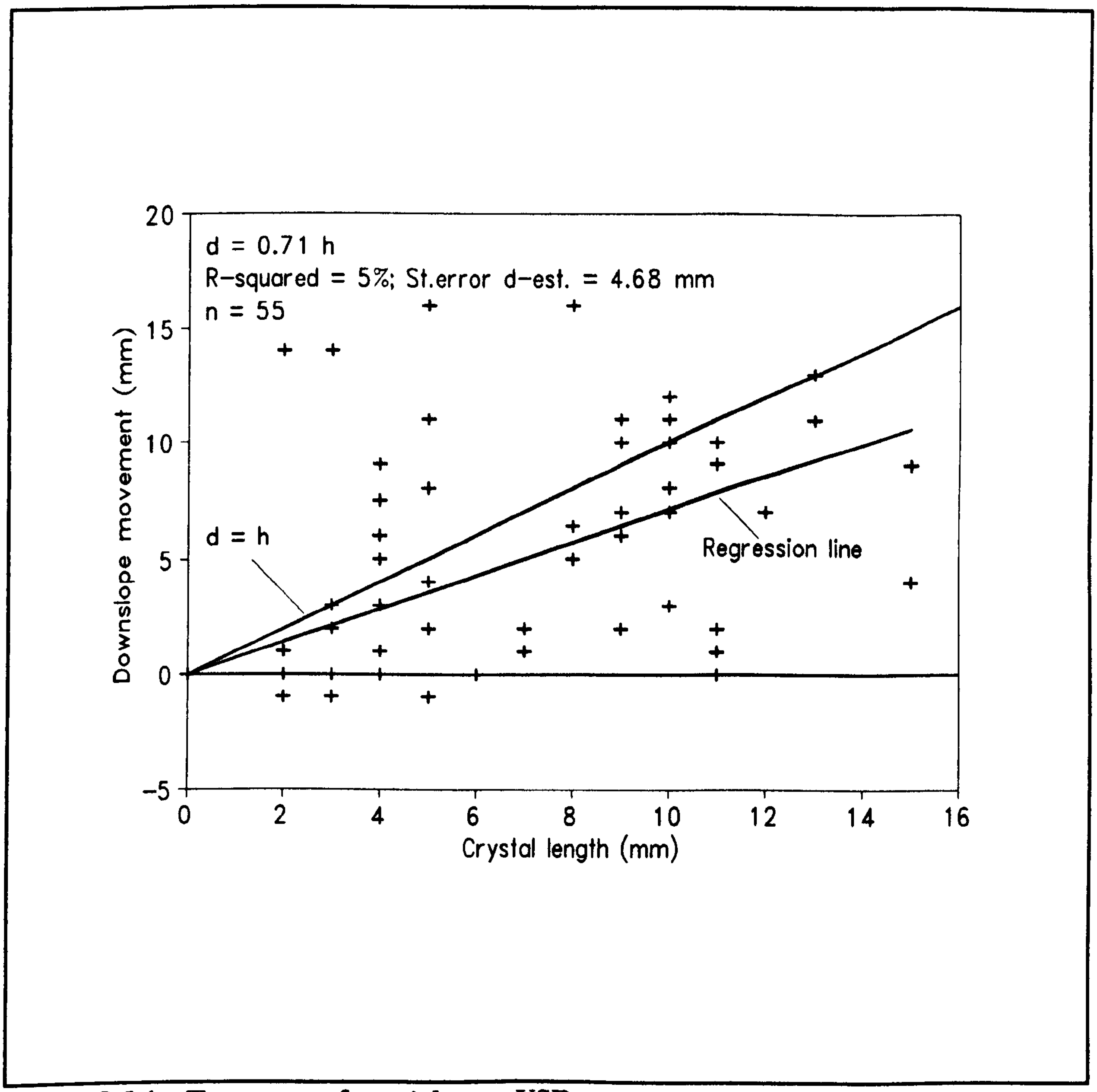

Figure 8.14 : Transport of particles on USB_2 **15°, stones**

it has toppled, but is only a tentative suggestion given the limited number of points greater than 17 mm. There is a large amount of scatter in the plot, this indicates that, contrary to the assumption of the toppling model (Section 3.3.1) crystal height is not the sole determinant of marker transport.

Details of the mean downslope movement on all slope angles is shown in Figure 8.16 and Tables 8.3 and 8.4. As expected, for equivalent lengths of needle-ice crystal, the markers were transported a greater distance as the slope angle increased. Again, however, there was a large amount of inter-particle variability of the relationship (Table 8.3). Figures 8.17, 8.18 and 8.19 show the distance of downslope movement on the 5°, 15° and 30° slopes. (These data are shown because they represent the minimum, maximum and intermediate slope angles used in this study.) Simple linear regression relationships between crystal height and transport were calculated for each slope angle (Figure 8.20). The equations and details of their statistical significance are shown in Table 8.4.

Figures 8.17 to 8.20 and the R^2 values of the equations in Table 8.4 show that as slope angle increases, the control of crystal length over downslope particle transport becomes more pronounced. The slope of the regression line on the 5° plot is strongly influenced by the two -4 mm points. When these points are removed from the analysis, the standard error of the equation is reduced and the R^2 is increased (Figure 8.17).

The h-coefficient increases as slope angle increases, until at 30° the closeness of the coefficient to unity indicates that the needles often topple. The relatively low value of the slope coefficients on the 5° and 6° slopes shows that the slope angle is not steep enough to force the needles to topple, also the needles often toppled upslope (e.g. Figure 8.17 and Section 8.3.5) or as much across the slope as downslope (Section 8.3.4). The relationships for the 6°, 15° and 30° slope

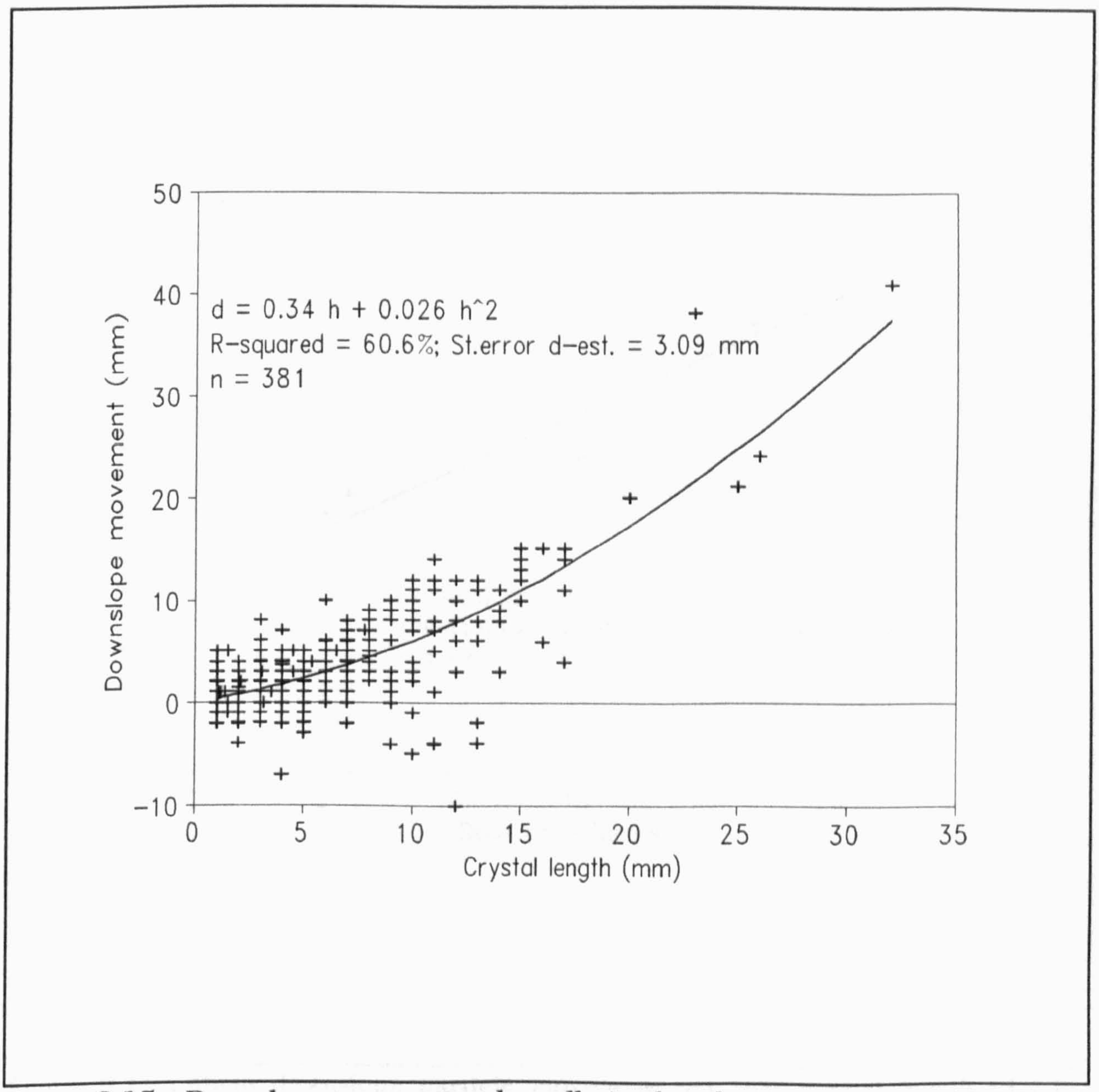

Figure 8.15 : Downslope transport and needle-ice length DSB_1 and USB_2, stones

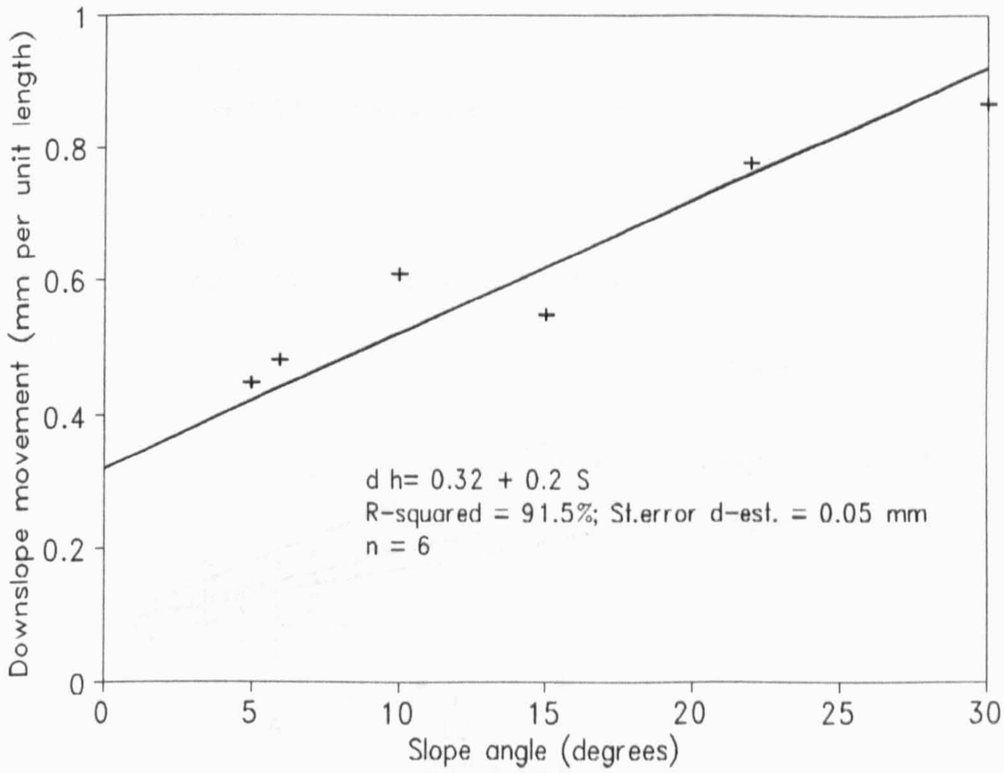

Figure 8.16 : Mean downslope particle movement per unit crystal length (d_h) for different slope angles **DSB_1, stones**

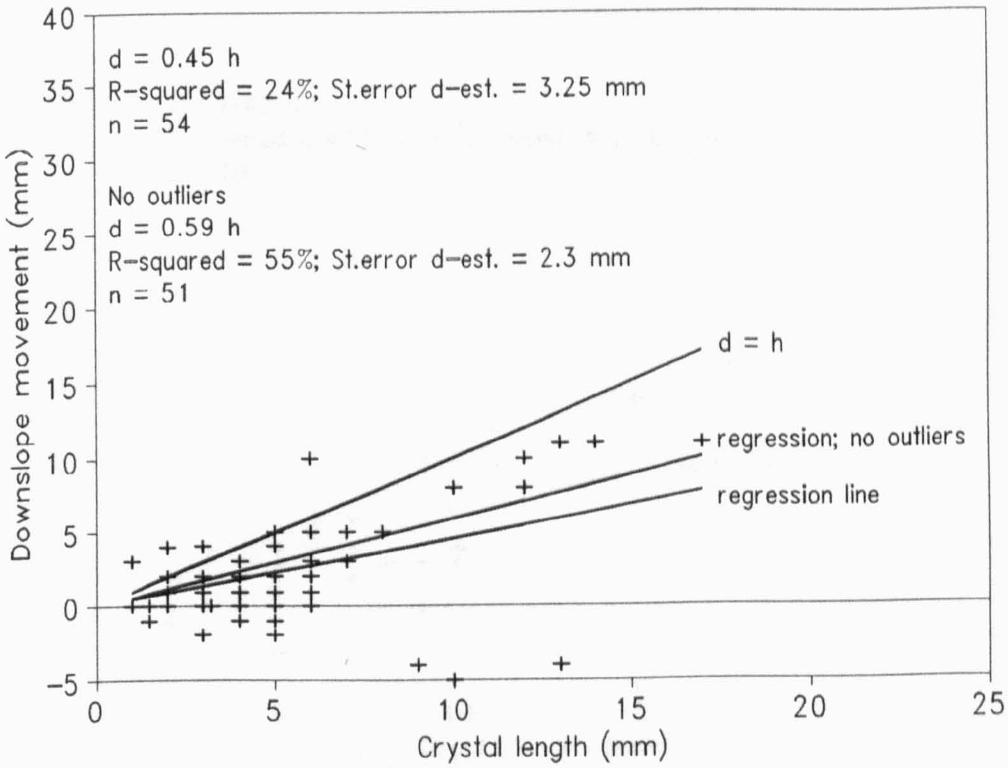

Figure 8.17 : Downslope movement on 5° slope **DSB_1, stones**

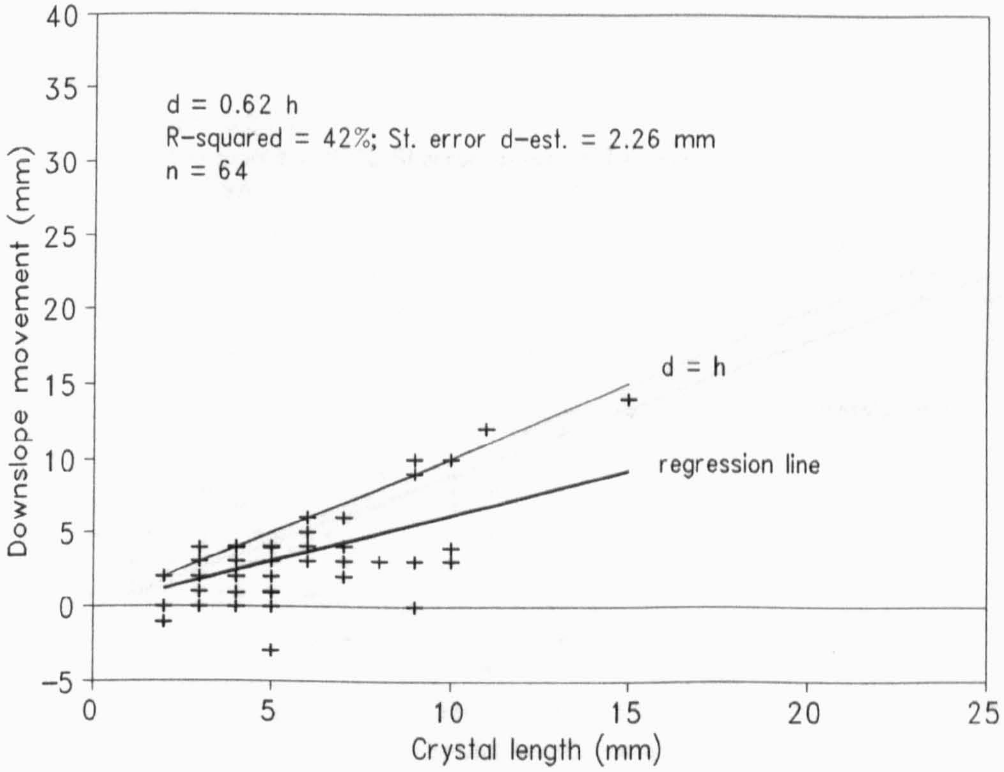

Figure 8.18 : Downslope movement on 15° slope **DSB_1, stones**

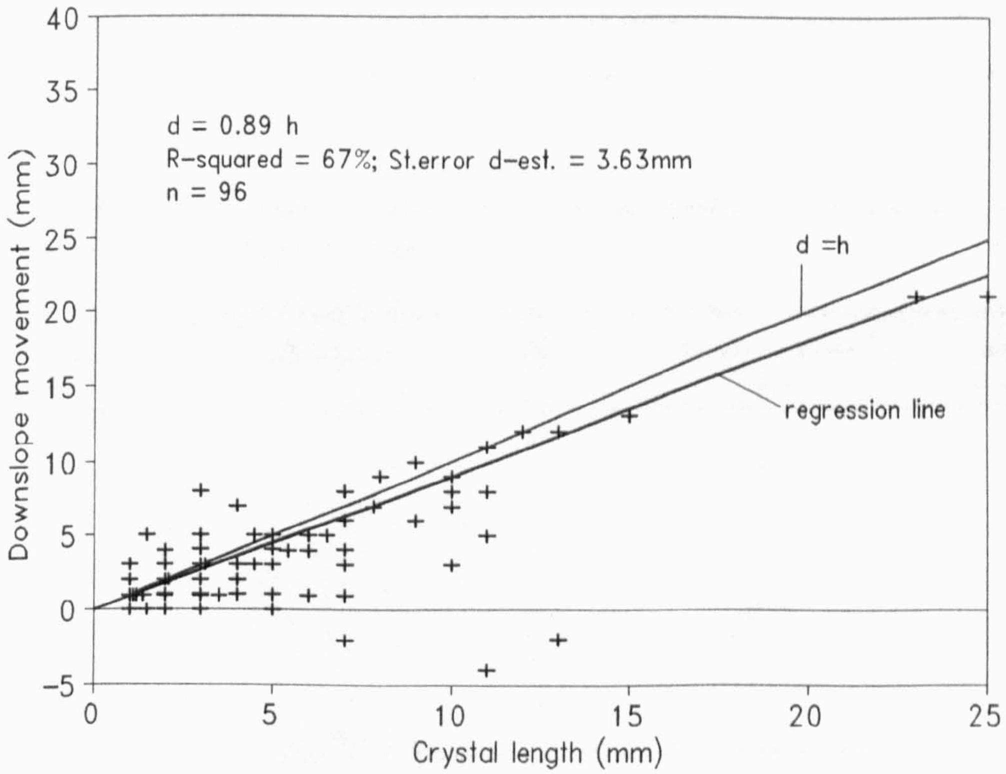

Figure 8.19 : Downslope movement on 30° slope **DSB_1, stones**

Table 8.3 : Downslope movement of particles on different slope angles

DSB_1, stones

Slope (°)	Marker movement per unit length of crystal (mm)[a]				no. of markers
	Mean	Minimum	Maximum	St.dev.	
5	0.44	-0.67	3.00	0.67	54
6	0.48	-2.00	3.00	0.80	75
10	0.61	-0.67	2.00	0.49	48
15	0.68	-0.60	1.33	0.44	64
22	0.77	-1.00	5.00	0.99	54
30	0.87	-0.36	3.33	0.64	96

[a]Data includes the effects of negative values and thus reflects the 'true' mean, min., max. and standard deviation of the data

Table 8.4 : Results of linear regression between needle-ice length and distance of marker transport on different slope angles

DSB_1, stones

Slope (°)	Equation	R^2 (%)	St. error d-est. (mm)	no. of markers
5	$d = 0.44\ h$	24	3.25	54
6	$d = 0.46\ h$	29	3.52	75
10	$d = 0.53\ h$	46	2.99	48
15	$d = 0.62\ h$	42	2.26	64
22	$d = 0.73\ h$	66	3.51	44
30	$d = 0.89\ h$	67	3.63	95

all significant at the 95% confidence level

angles shown in Table 8.4 will be developed in Section 9.4 as part of a new model of needle ice sediment transport.

8.3.2 Process of needle-ice melt and soil type

The markers lifted by needles that toppled were transported further than those markers lifted by needles that gradually melted. As a result, under the same growth conditions (in terms of

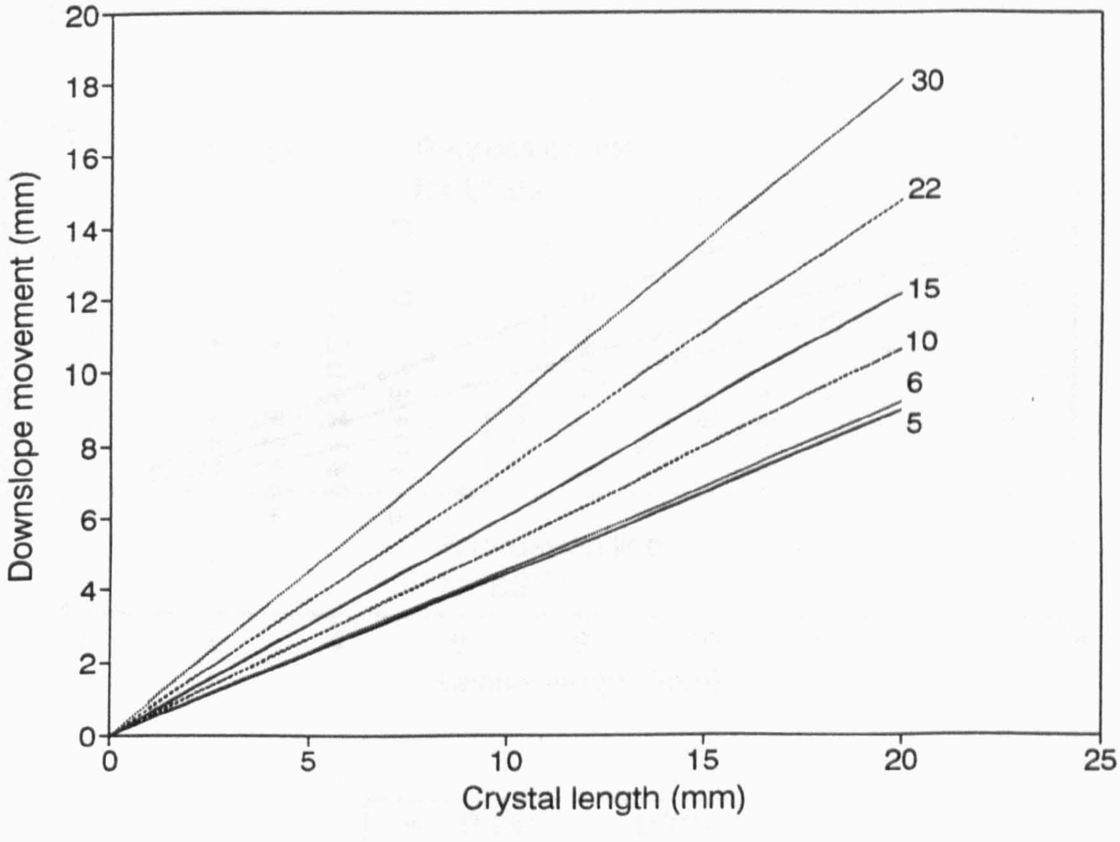

Figure 8.20 : Regression lines of crystal length and downslope movement for different slope angles

DSB$_1$, stones

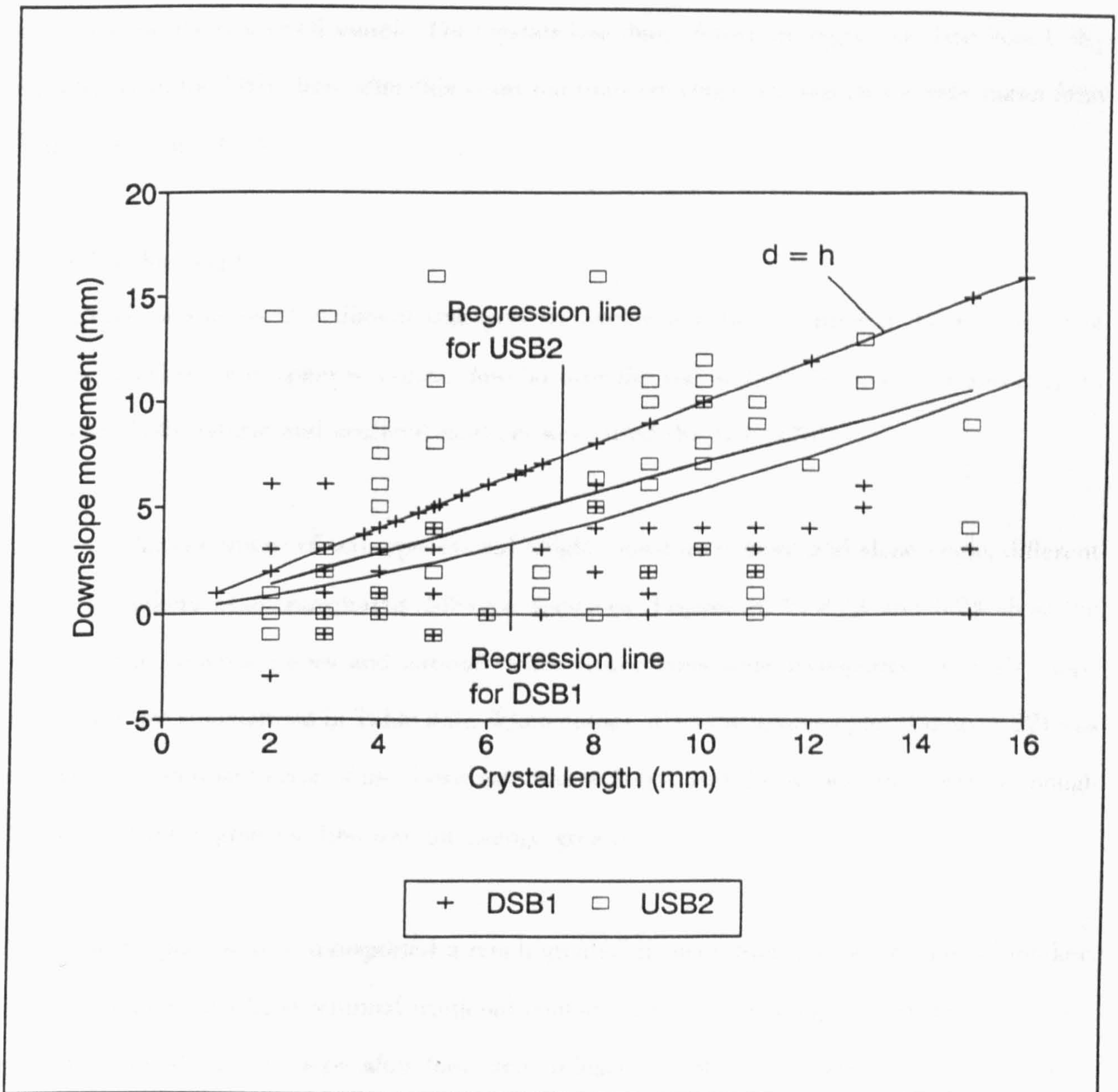

Figure 8.21 : Distance of sediment transport, DSB_1 and USB_2

(15°, stones)

moisture content, slope, etc.), given that needles on USB_2 usually toppled (Section 8.2), the markers were transported a greater distance than markers on DSB_1 where the needles often melted back onto similar positions from which they were lifted. Figure 8.21 shows that for an equivalent height of crystal, the markers on the undisturbed samples were usually moved further than those on the disturbed sample. For crystals less than 16 mm the regression line from USB_1 is higher than the DSB_1 line, after this point the lines converge (the equations were taken from Figures 8.13 and 8.14).

8.3.3 Marker type

Most previous studies of sediment transport by needle ice have monitored the movement of artificial markers (e.g. spheres, cubes, dowels) over the soil surface (Sections 4.4 and 5.5). In this study both natural and artificial markers were used (Section 5.5.2).

Under similar conditions of soil type, crystal height, moisture content and slope angle, different types of markers were transported different distances. Figures 8.22, 8.23 and 8.24 show the distance that spheres, cubes and natural stones respectively were transported on a 15° slope (these data are summarised in Table 8.5). When outlier 'a' on the spheres plot (Figure 8.22) was removed, the standard error of the d-estimate was reduced, and the R^2 was increased, although the slope of the regression line did not change greatly.

On average, spheres were transported a much greater distance than the other types of marker. This is because they have minimal frictional contact with the 'receiving' soil surface, and they tended to roll down the slope after they were released by the ice crystals. There was also a greater amount of variability of the movement of spheres than of cubes and stones (Table 8.6). This is simply because some spheres rolled and others did not, depending on the essentially random micro-scale irregularities of that part of the soil surface to which they 'returned' after heaving.

Table 8.5 : Regression equations of the relationship between crystal length and downslope movement for different marker types

Type of marker	Figure no.	Equation no.	R^2 (%)	St.error of d-estimate (mm)	no. of markers
Spheres	8.22	$d = 1.59\ h$	52.9	9.45	39
Spheres (no outlier)	8.22	$d = 1.54\ h$	75.5	6.19	38
Cubes	8.23	$d = 0.95\ h$	93.6	1.87	48
Stones	8.24	$d = 0.59\ h + 0.01\ h^2$	88.0	2.38	64

Table 8.6 : The movement of different types of marker particle **DSB_1, 15°**

Marker type	Figure no.	Downslope movement per unit length of crystal (mm)[a]				no. of markers
		Mean	Minimum	Maximum	St. dev.	
Spheres	8.22	1.68	0.00	14.29	2.18	39
Stones	8.23	0.53	-3.00	1.33	0.60	64
Cubes	8.24	0.85	-0.30	1.50	0.41	48

[a] data includes the effects of negative values and thus reflects the 'true' mean, min, max and standard deviation

Spheres thus moved considerably greater distances than the natural particles. The results of previous studies which used spheres as markers may therefore over-estimate the rate of movement of natural particles over the soil surface. This is a problem of experimental geomorphology (Chapter 4), i.e. deciding whether it is preferable to remove the random element by using uniform markers or natural markers or whether identical, but naturally-shaped markers, manufactured to identical specifications should be used in an attempt to replicate 'real' conditions as closely as possible.

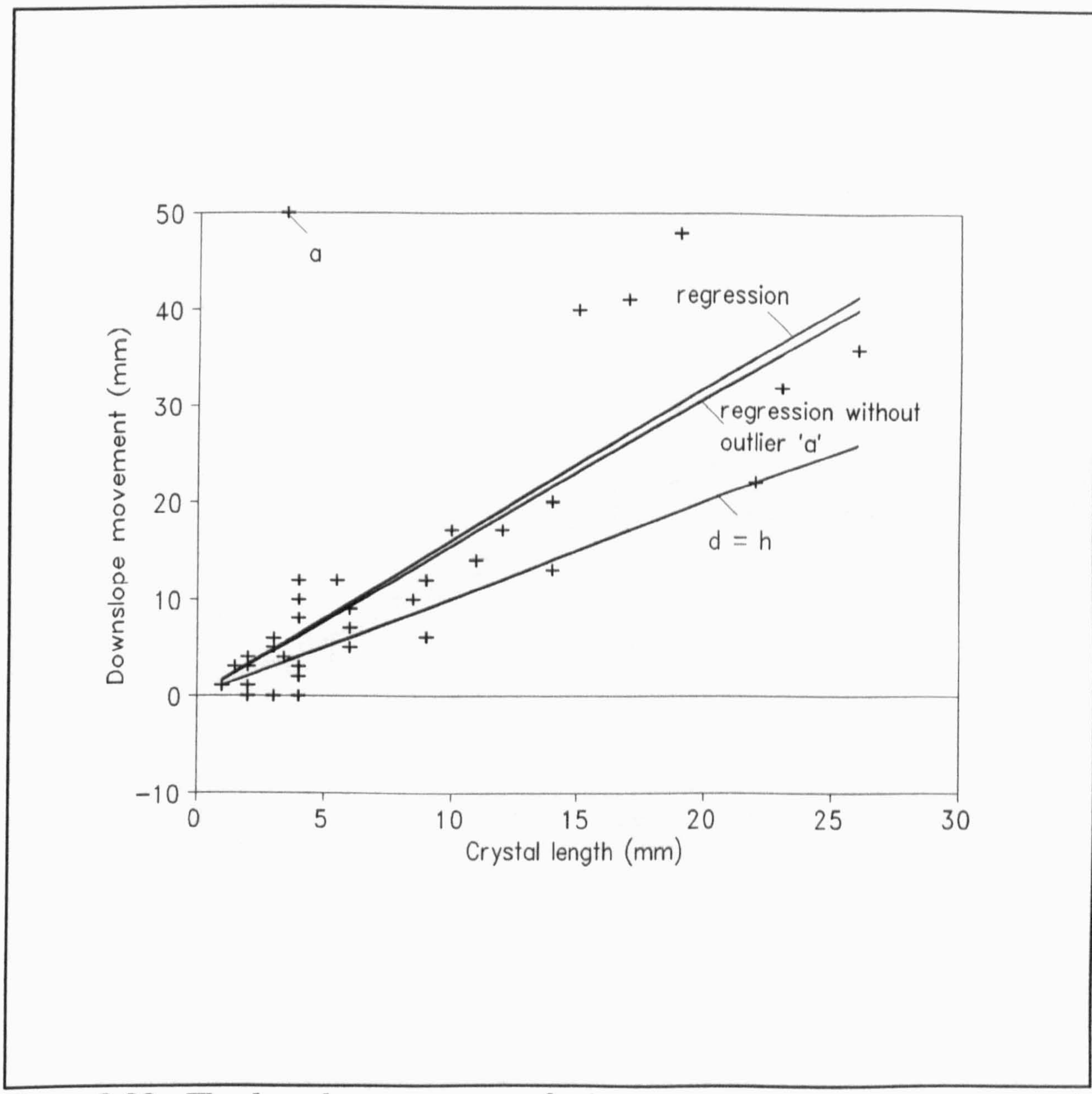

Figure 8.22 : The downslope movement of spheres **(DSB$_1$, 15°)**

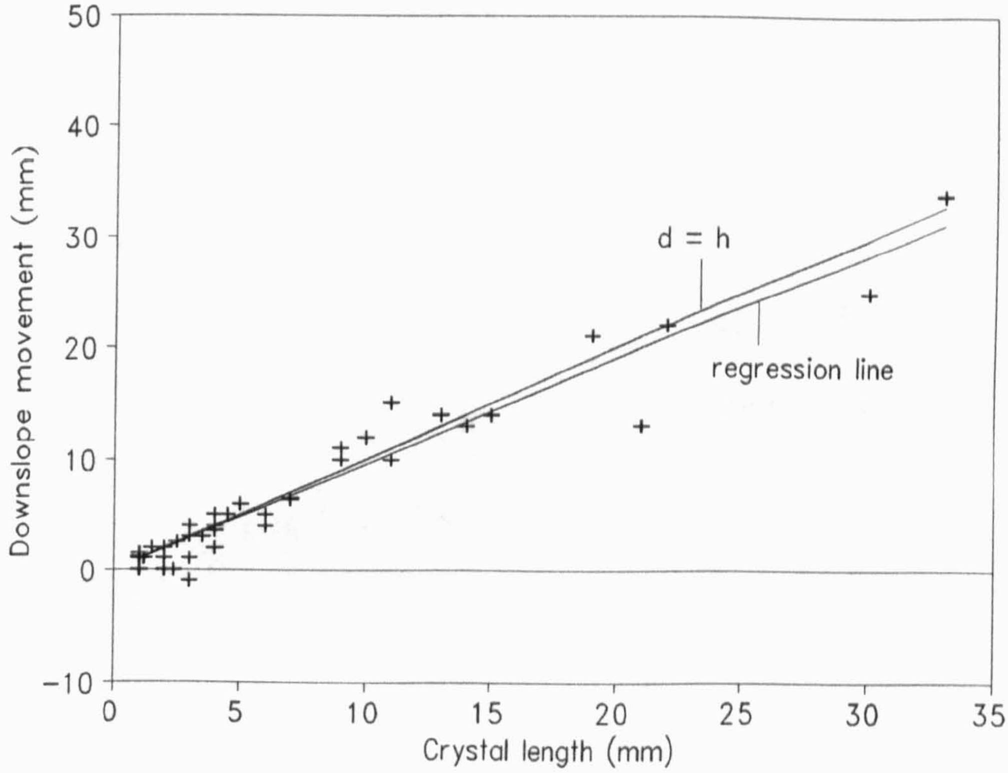

Figure 8.23 : The downslope movement of cubes **(DSB_1, 15°)**

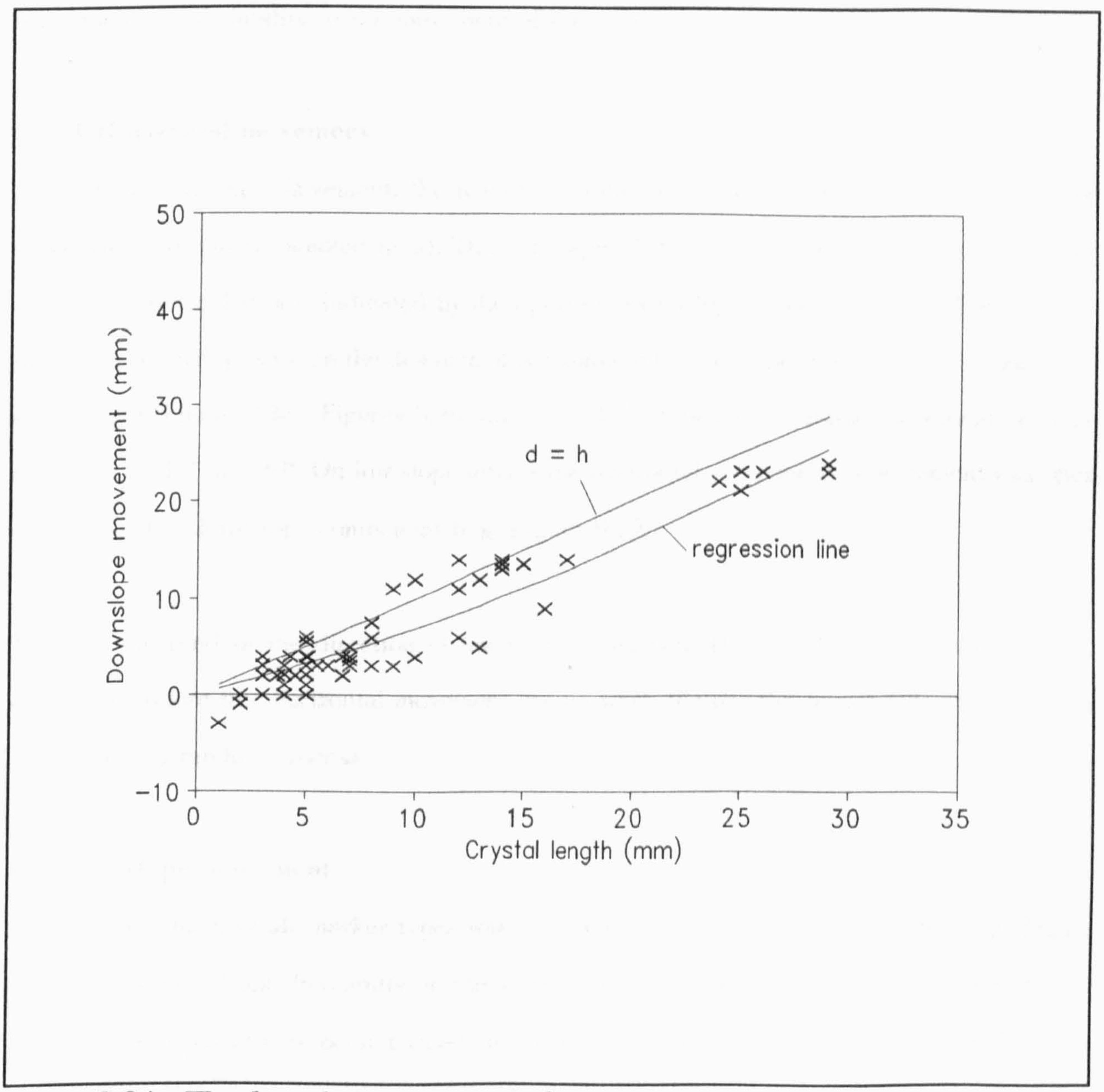

Figure 8.24 : The downslope movement of stones **(DSB_1, 15°)**

There was a large amount of variability in the movement of the stones even under similar growth conditions. When the stones were selected an attempt was made to ensure that they had the same size and shape (Section 5.5.2). However, there was variability between the characteristics of the stones and this probably explains some of the inter-marker movement differences. There was much less variability in the movement of the cubes.

8.3.4 Horizontal movement

As well as downslope movement, the marker particles were also transported across the slope (horizontal movement, denoted by a). Thus, the total distance of marker transport on the slope was often greater than was indicated by the figures of downslope movement alone. There was an inverse relationship between the distance of horizontal movement (per unit length of crystal) and slope angle (Figure 8.25). Figures 8.26, 8.27 and 8.28 show the horizontal movement on slope angles of 5°, 15° and 30°. On low slope angles the horizontal component of movement was often as great as the downslope component (e.g. Figure 8.29).

There is no trend in the direction of horizontal movement (Figures 8.26, 8.27 and 8.28). It appears therefore that horizontal movement occurs when the needles topple sideways, and this seems to be a random process.

8.3.5 Upslope movement

Upslope movement of all marker types was common on the 5°, 6° and 10° slopes (e.g. Figure 8.17) and occurred less frequently on the steeper slope angles (e.g. Figure 8.19). This type of movement has sometimes been termed 'retrograde movement' (e.g. Washburn, 1967, 1979; Ahnert, 1971), and various theories have been suggested to explain its occurrence. Ahnert (1971) stated that it was a result of cohesion and interference between particles, whilst Washburn (1967) suggested that it may be related to capillary pressures. Jahn (1975) allowed for retrograde movement in the transport equation by including a coefficient of adhesion (it was

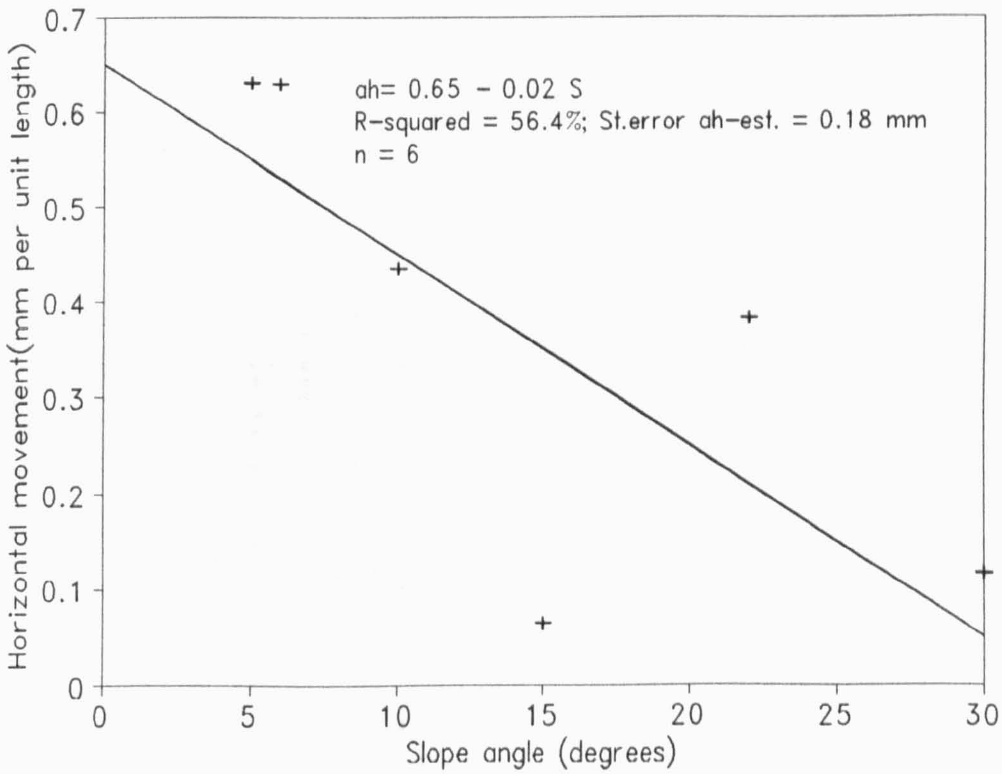

Figure 8.25 : Mean horizontal movement per unit crystal length (a_h) for different slope angles **DSB_1, stones**

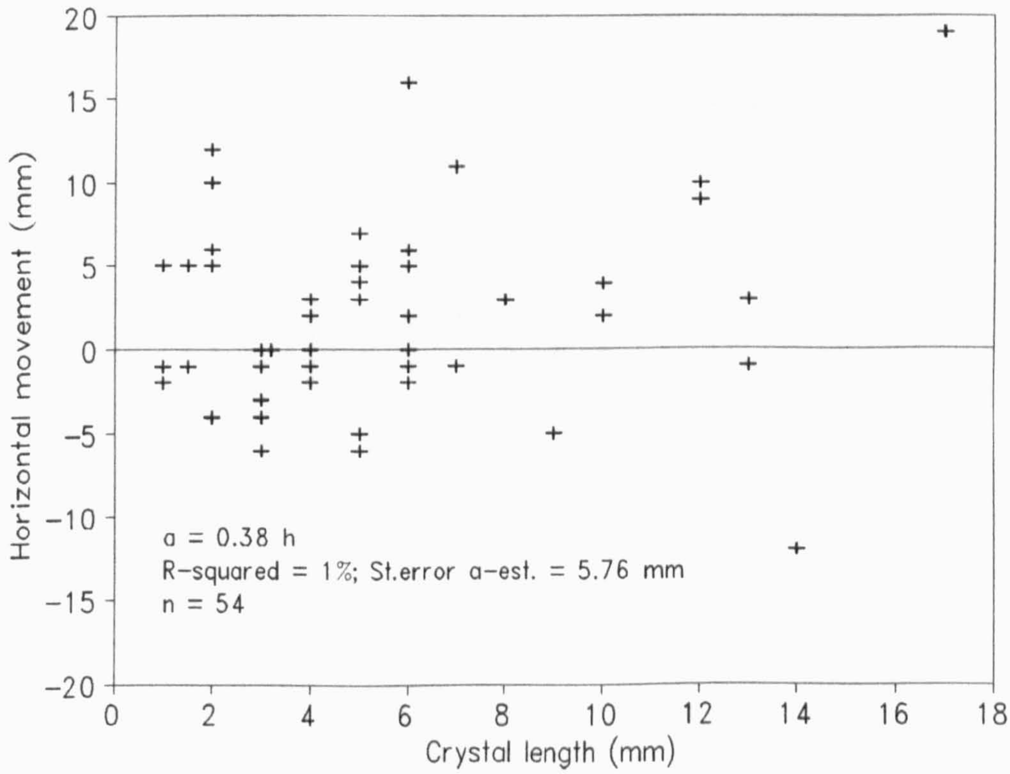

Figure 8.26 : Horizontal movement on 5° slope **DSB_1, stones**

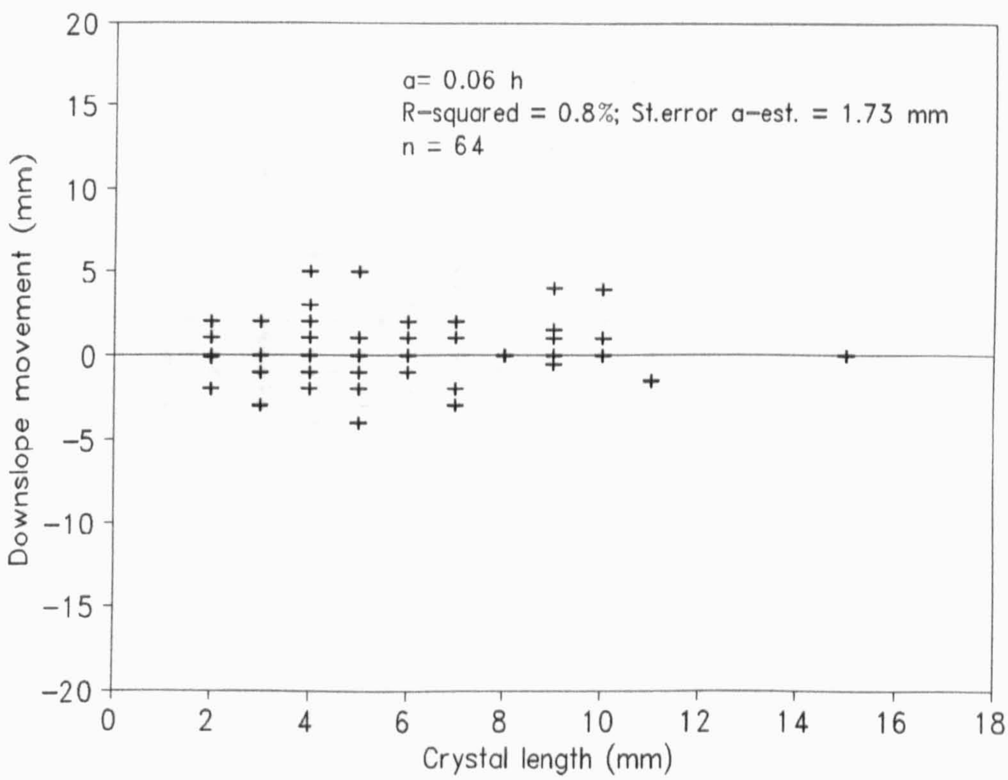

Figure 8.27 : Horizontal movement on 15° slope **DSB_1, stones**

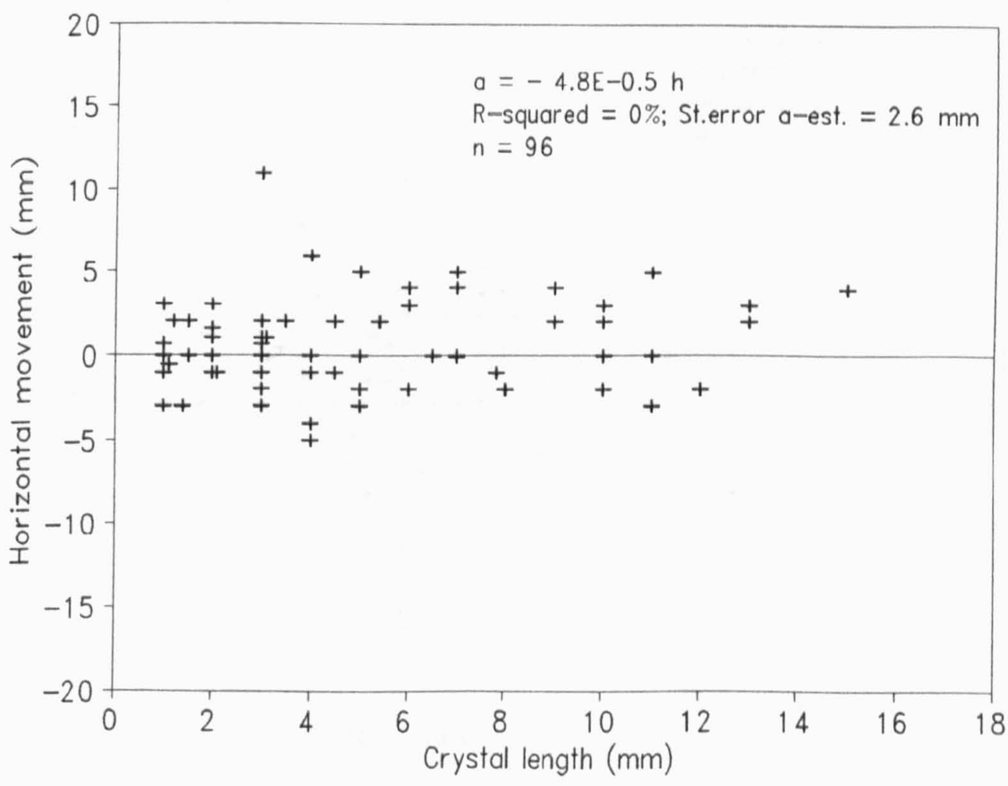

Figure 8.28 : Horizontal movement on 30° slope **DSB_1, stones**

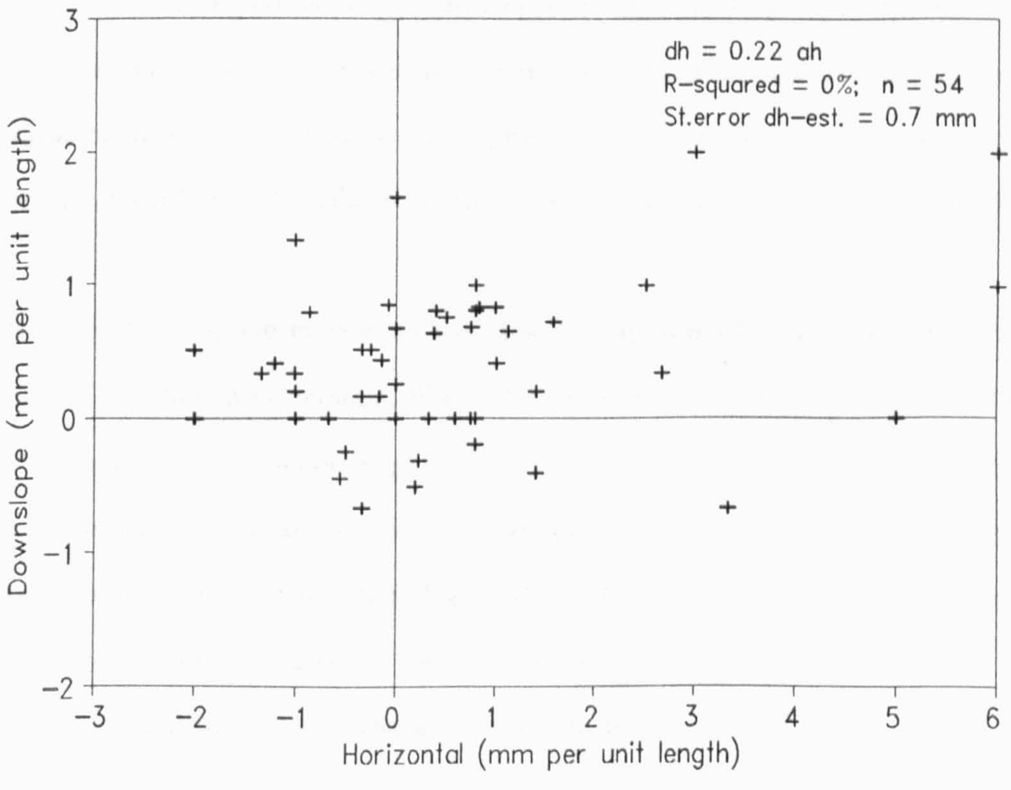

Figure 8.29 : Horizontal and downslope movement on the 5° slope

DSB_1, stones

not stated on what this was based), thus

$$d = kh(\tan S) \qquad (8.1)$$

where k is the coefficient of adhesion.

The markers used in most of the laboratory experiments were natural stones, and thus it is not thought that cohesion or capillary pressure caused the retrograde movement. Upslope transport usually occurs on low angled slopes, when it appears that the slope has little influence on the direction that the needles fall, and is thus probably a result of the needles falling randomly onto the soil surface. (In the field needles may topple upslope if melting is influenced by the effect of wind or direct sunlight.) Alternatively, the crystals may have grown curving upslope.

The occurrence of retrograde movement may also be explained by the way in which the stones rest on the top of a bunch of crystals. When the stone rested on the crystals such that most of its weight was concentrated on one edge of the crystal, then preferential pressure-melting on that edge caused the stone to tilt and eventually slide or topple off the crystals. The stone was then often upslope from where it was lifted (Figure 8.30). On steeper slopes this 'pressure melting' effect is probably counterbalanced by the influence of the slope itself, and thus the stones still fall downslope regardless of where the stone rests on the crystal.

It is also possible that upslope movement could arise during the growth of crystals. Direct observation of the crystals whilst they grow and ablate is necessary to determine whether growth or melt caused the upslope movement, and is an area of research that would benefit from the use of time-lapse photography or video (Section 10.4).

8.3.6 Influence of location of sediment within the ice crystal on marker movement

A small number of experiments were carried out to determine if the distance that the sediment was transported was controlled by the location of the sediment within the ice crystal. (This area

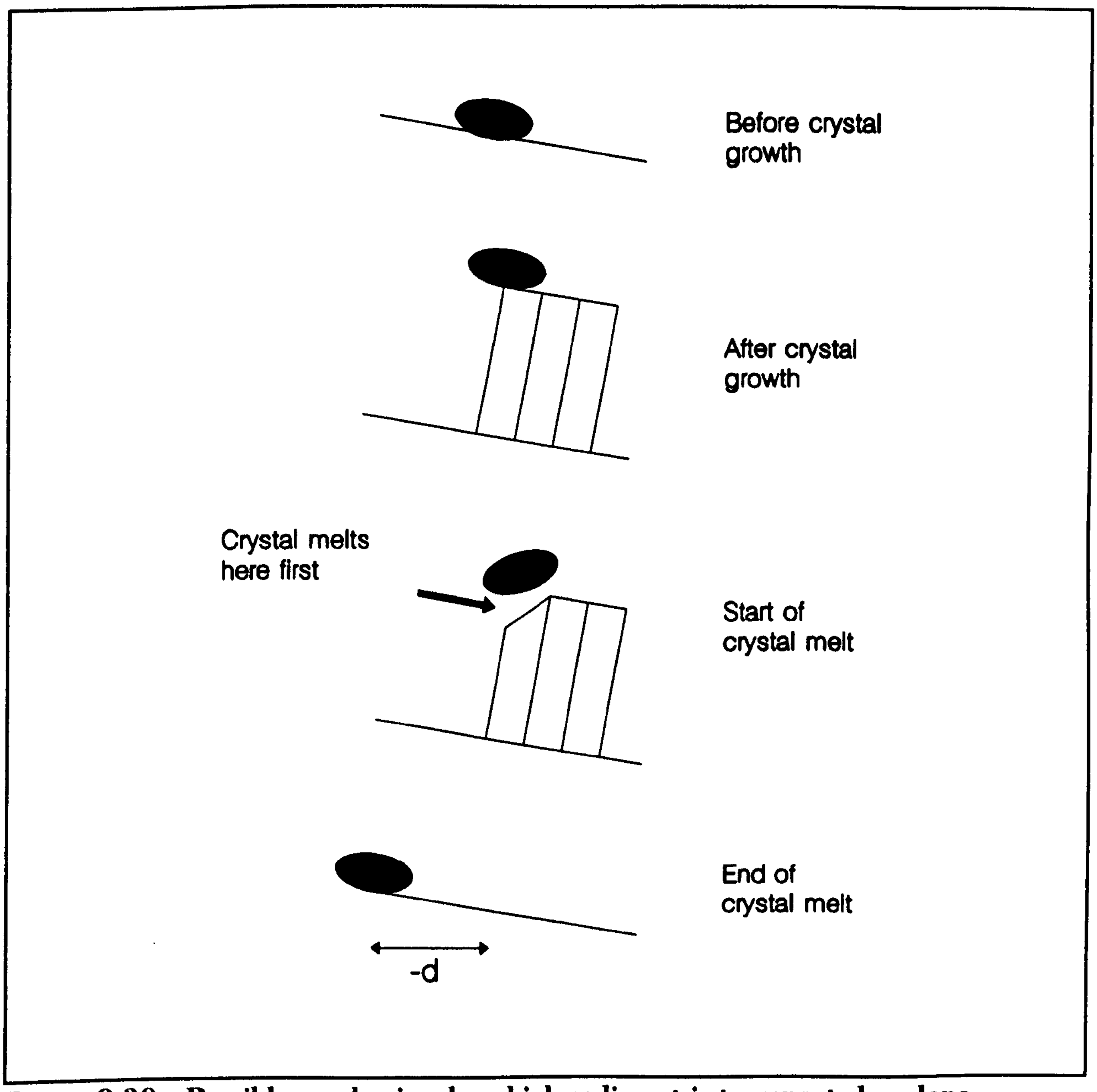

Figure 8.30 : Possible mechanism by which sediment is transported upslope

of research is important because all previous models of transport (e.g. the gravity-fall and toppling models - see Sections 3.3.1a and 3.3.1b) use the total height of the crystal to estimate how far markers are displaced, and thereby assume that all sediment is transported from the soil cap.) These experiments were not completely successful (Section 5.5) but the preliminary findings showed that sediment which is incorporated within the crystal moved much shorter distances than sediment that rested on top of the crystal. This will be particularly evident when the ice crystals topple before melting, as the sediment within the crystal will obviously fall a smaller distance than the sediment on top of the crystal. This is clearly an area for future research (Section 10.4).

8.4 CONCLUSIONS

In the laboratory three types of needle-ice melt were observed: toppling, gradual melt and a fracture-collapse process. Toppling was common on the undisturbed soil sample and caused markers to be transported further than those on the disturbed sample (which were usually released by gradual melt). Long crystals on both samples commonly broke off near to the top and then gradually melted.

The rate of needle-ice melt seemed to be influenced by the energy balance at the soil surface and the location of sediment within the ice crystal. If soil caps were present the crystals usually melted slowly, whereas when sediment was included into the crystals the ice melted faster than clear crystals of equal height.

Crystal height, slope angle, the process of needle melt, marker type and type of ice crystal were found to affect the distance of sediment transport. Upslope movement and the movement of markers across the slope was also common. On low slope angles the horizontal component of movement was often as great as the downslope movement.

Chapter 9

MODELS OF THE GROWTH AND MORPHOLOGICAL EFFECTS OF NEEDLE-ICE GROWTH

9.1 INTRODUCTION

In this chapter the results of the needle-ice experiments presented in Chapters 6, 7 and 8 are analysed in more detail, and an attempt is made to represent the growth and morphological affects of needle ice in a series of models. The chapter is split into three main sections which discuss:

i) the rate of needle-ice growth;

ii) controls on the amount of sediment incorporated by needle ice;

iii) sediment transport by needle ice.

Each section discusses how the particular process has been represented by other authors and examines the validity of these approaches for the present study. New statistical models are then presented which attempt to improve the level of prediction of the process for the laboratory experiments, using types of data that have not previously been incorporated into models of needle ice. Suggestions as to how these new models could be developed in future studies and the wider implications of the models are made in Chapter 10.

Unless stated, the data are from both disturbed and undisturbed samples. Where the regression relationships are significant at the 95% confidence level, the regression line is shown on the scatter plots.

9.2 PREDICTING THE LENGTH OF NEEDLE-ICE CRYSTALS

9.2.1 A simple representation of needle-ice length

Lawler (1984, 1987), used data from needle ice grown on the bank of the River Ilston in South Wales to derive the following empirical relationship

$$h = -2.78 + 0.962 D_0 \tag{9.1}$$

where h is the length of needle ice (mm) and D_0 the duration of sub-zero temperature (hours).
(R^2 = 87.6% ; n = 71 ; significant at 99% confidence level.)

The temperature data were taken from an air thermograph c.3 km away from the river bank. The threshold of 0°C was chosen because it approximately correlated with a temperature of -2°C on the river-bank surface (assumed to be the ice nucleation temperature). Lawler (in press) suggested that the negative constant in this equation 'implies that almost three hours of sub-zero air temperatures are required before needle growth is initiated, which may be related to the time-lag inherent in river bank thermal response and/or moisture migration to the freezing front'.

The approach of Lawler was used to represent the length of needle ice in the laboratory. As the soil-moisture content, soil properties and cooling mechanisms in the laboratory differed from those in the Ilston field site, it was necessary to determine the soil-surface temperature that was most strongly related to needle length in these experiments. This was achieved by correlating needle length against the number of hours that the soil-surface temperature was below a given threshold. The highest correlation was found between crystal length and the time that the soil-surface temperature was below -1.5°C. This produced the following relationship (shown in Figure 9.1)

$$h = 5.96 + 0.368 D_{1.5} \qquad (9.2)$$

where $D_{1.5}$ represents the number of hours that soil-surface temperature was below -1.5°C. (R^2 = 10.2%; St.error h-est. = 7.75 mm; n = 152; significant at 95% confidence level.)

This equation, although statistically significant, has a high standard error and a very low R^2 when compared to that of the Ilston study. In the following section a new semi-empirical model for predicting needle-ice length in the laboratory based on multiple regression analysis is presented. A discussion of the advantages and disadvantages associated with multiple regression is not presented here as it is discussed adequately elsewhere (e.g. Till, 1973; Hauser, 1974; Ferguson, 1977; Anderson and Cox, 1984).

9.2.2 Improving the level of prediction for the laboratory study

9.2.2a Problems with the relationship between h and $D_{1.5}$

There are two main problems with the form of equation as shown in Equation 9.2 with respect to the laboratory study:

i) it assumes that needle ice grows continuously once the ice nucleation temperature is reached. In Chapters 6 and 7, however, it was argued that growth was often disturbed. Thus, it is recommended that the model should be extended to include a component which represents cessation of needle-ice growth;

ii) the R^2 value is very low. The difference in the R^2 values of Equations 9.1 and 9.2 probably illustrates an important difference in the growth conditions between the field and laboratory sites. At the Ilston field site, given the throughflow from the surrounding slopes and the high river stage (Lawler, 1984, 1987), the supply of moisture was probably not a limiting factor. In the

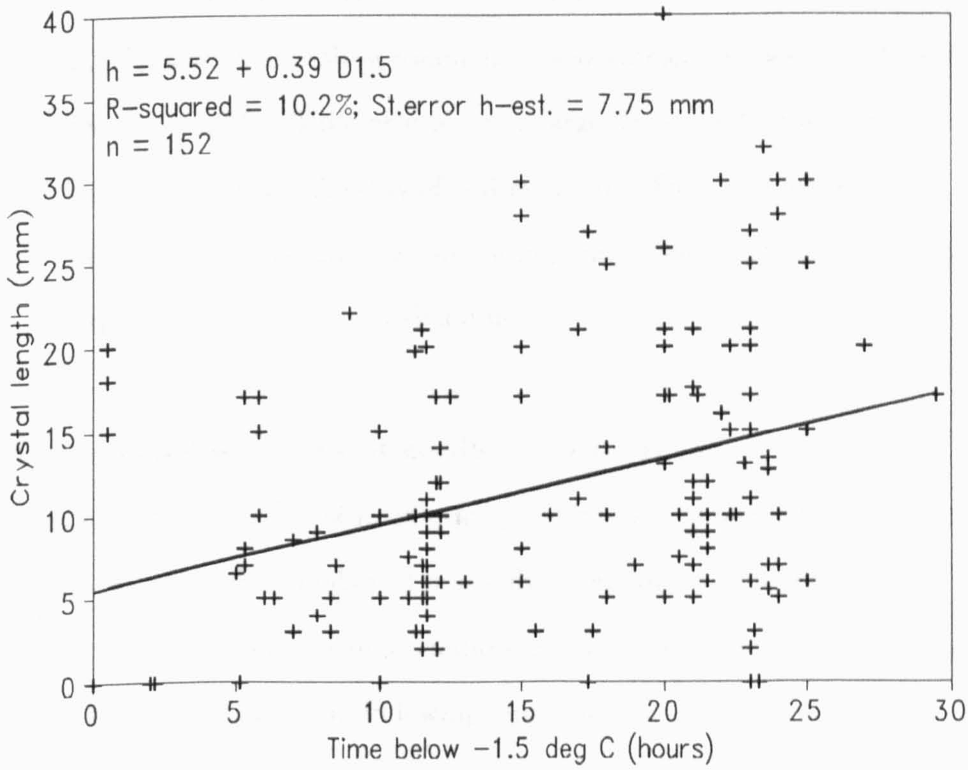

Figure 9.1 : The relationship between crystal length and $D_{1.5}$

laboratory, however, the moisture supply was often deliberately restricted (e.g. Sections 5.3.2 and 7.3.1). Thus, in the laboratory the relationship between soil-surface temperature and needle-ice growth was affected, whereas in the Ilston site temperature was probably the only factor that limited growth. For laboratory experiments and field situations where moisture content is limited it is therefore necessary to include a component in the model that represents soil moisture.

Soils with a low soil-moisture content have a low thermal conductivity (Section 2.3.2), and once cooling commences soil-surface temperature decreases rapidly (Section 6.2.5). This results in a large $D_{1.5}$, and small needle-ice crystals (given the low availability of soil moisture). Thus, it appears that if moisture is in limited supply, analyses including temperature details only, as presented in Equation 9.2, may be misleading.

9.2.2b A new model to represent needle-ice growth

In the new model, the cessation of needle-ice growth was represented by the introduction of component D_5, which is the number of hours that soil-surface temperature was below -5°C (the average temperature below which needle-ice growth ceased). This had a negative affect on needle-ice length and gave the following equation

$$h=a+bD_{1.5}-cD_5 \tag{9.3}$$

where a, b and c are constants.

This was simplified to

$$h=a+bD_5 \tag{9.4}$$

where D_s represents the 'segregation time', i.e. the number of hours that soil-surface temperature was between -1.5°C and -5°C.

When tested on the data this gave the following (shown in Figure 9.2).

$$h\text{-}4.17+0.934D_s \tag{9.5}$$

This equation reduced the standard error of the length prediction and increased the R^2 value (Figure 9.2) when compared to Equation 9.2.

In the second stage of the model, taking account of the recommendations made in Section 9.2.2a, the moisture content of the soil surface at the start of the experiment was also included because of its strong relationship to crystal length (Figure 9.3.) This gave the following

$$h\text{-}-6.09+0.663D_s+0.312M_s \tag{9.6}$$

(R^2 = 64.7%; St.error h-est. = 4.9 mm; n = 152; significant at 95% confidence level).

This equation reduced the standard error and increased the R^2 when compared to Equation 9.5. Figure 9.4 shows the relationship between needle-ice length and soil-moisture content and segregation time. The actual and predicted lengths are shown in Figure 9.5. Possible future developments to this model are discussed in Chapter 10.

9.2.3 Prediction of crystal growth rate during two typical experiments

The controls on the rate of needle-ice growth in individual experiments discussed in Section 6.3.3 (Experiments 14/3/91 and 30/1/91) were investigated quantitatively using multiple regression analysis.

The data used in the following analysis is the hourly running mean of the change in moisture content near the soil surface (ΔM_1; % dry weight), soil-surface temperature (ΔT_s; °C) and

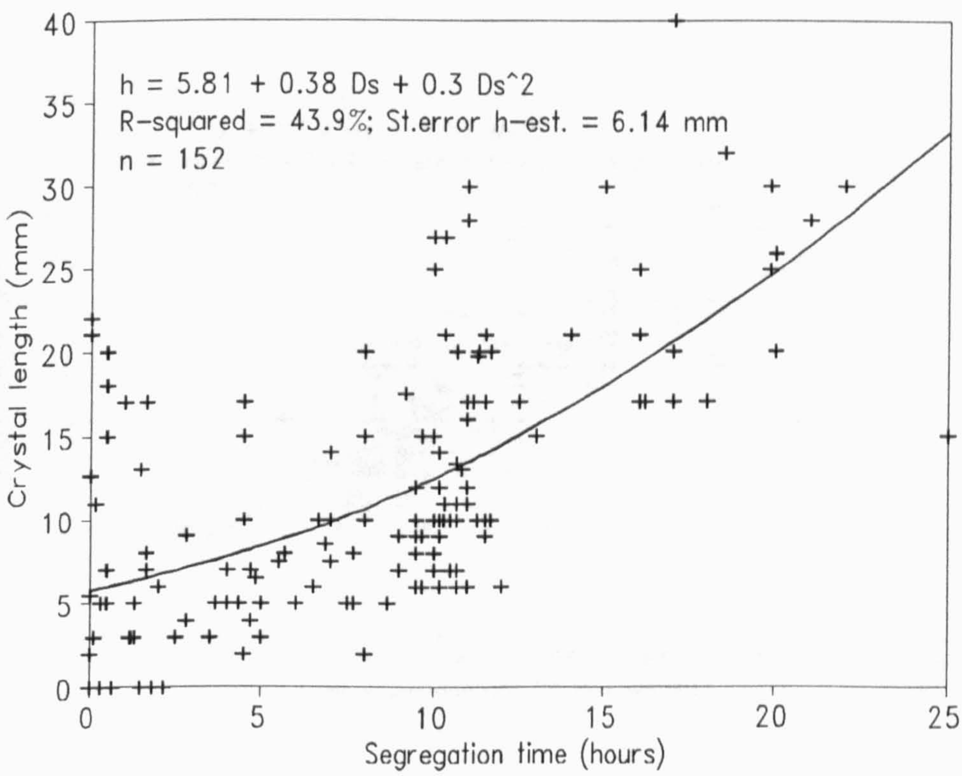

Figure 9.2 : The relationship between crystal length and 'segregation time'

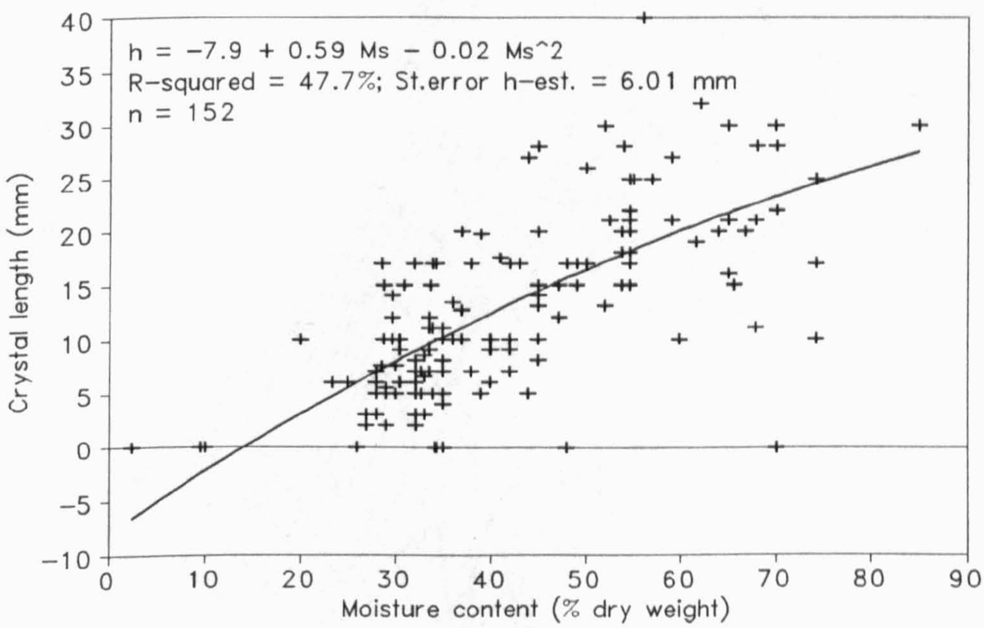

Figure 9.3 : The relationship between crystal length and soil-moisture content

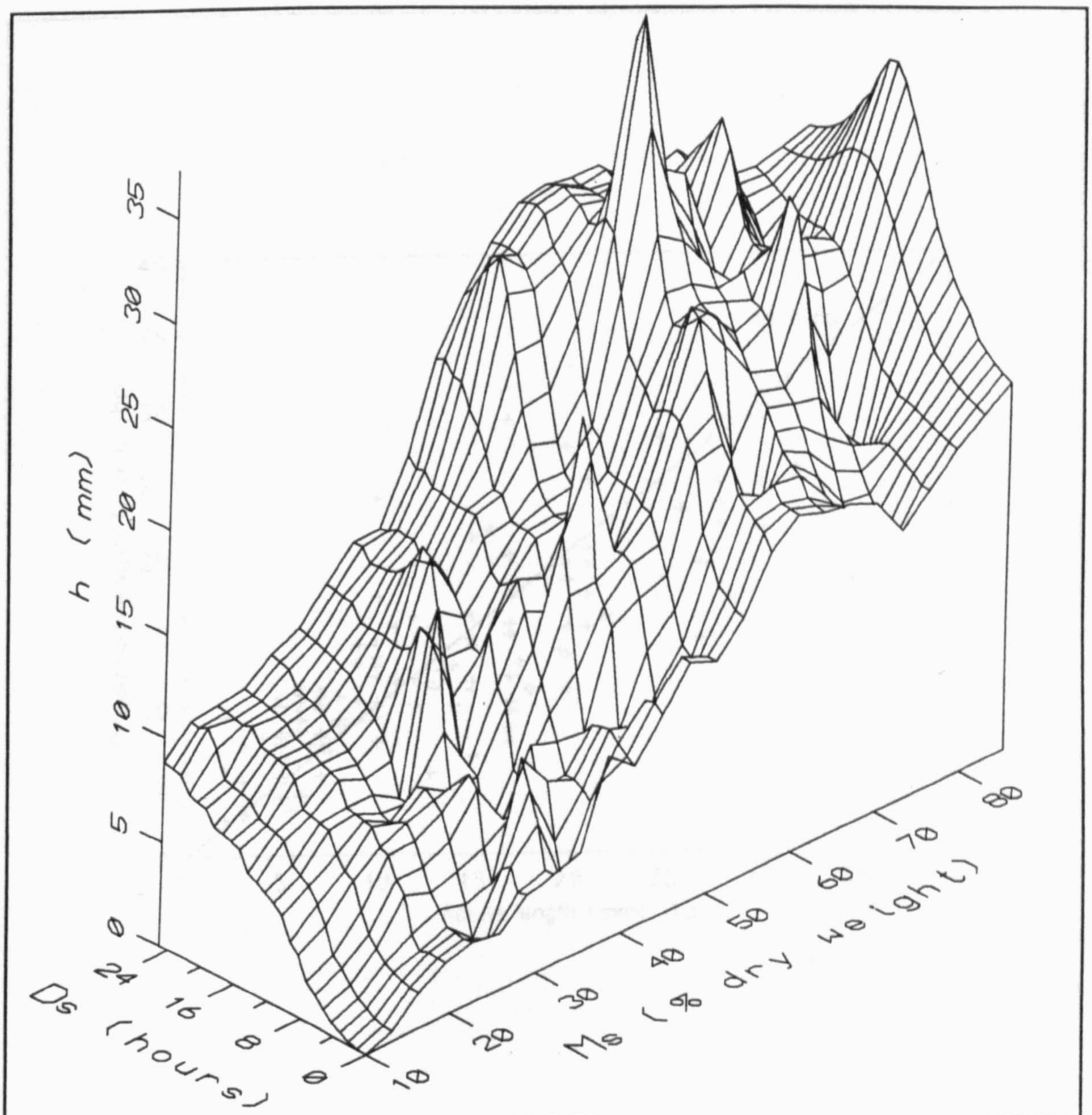

Figure 9.4 : The relationship between crystal length and soil-moisture content and segregation time

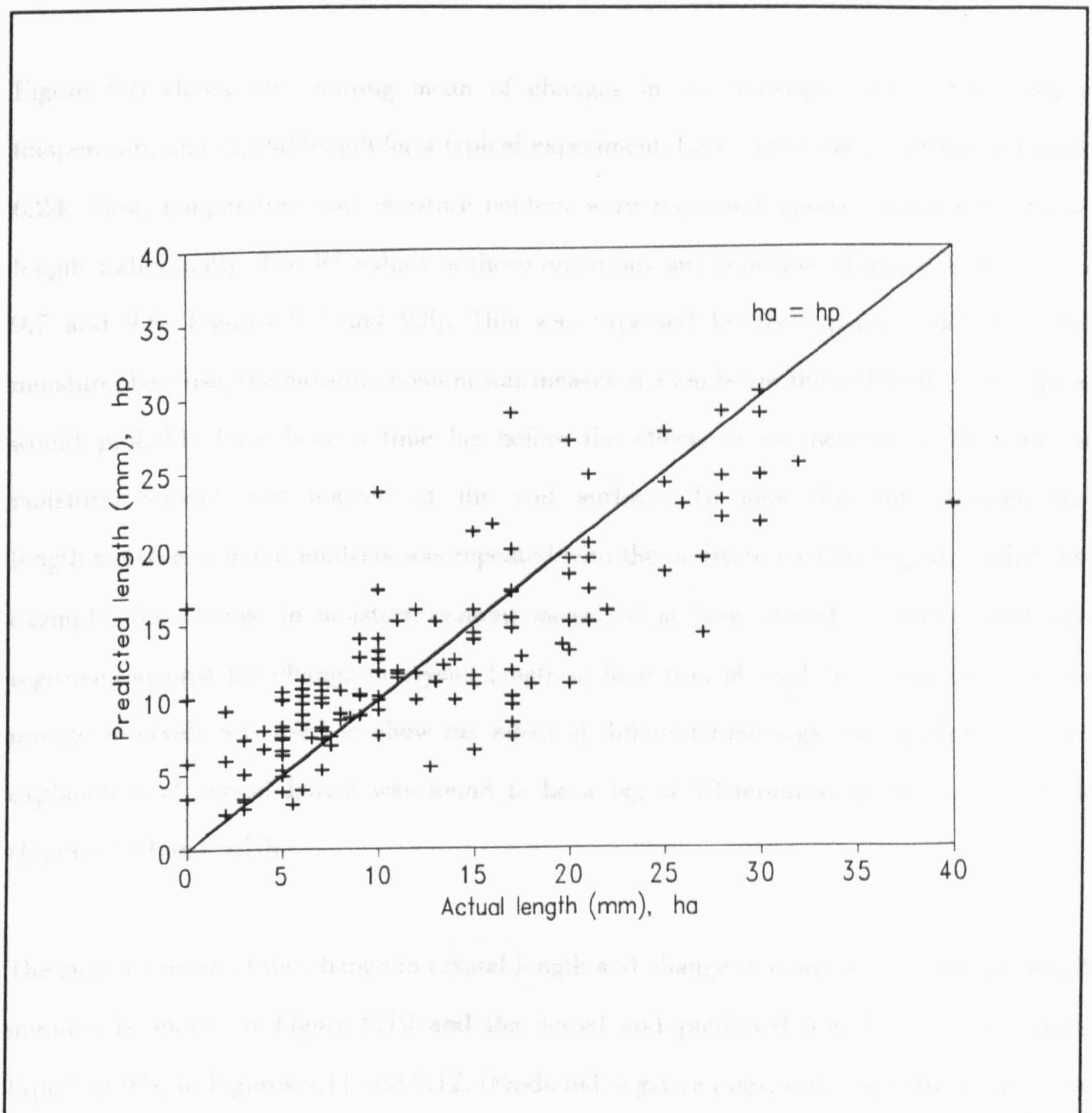

Figure 9.5 : The relationship between actual (h_a) and predicted (h_p) crystal length

crystal length (Δh; mm). Measurements were taken every 2 minutes, so the running mean averages 30 values. The use of this method smooths the data and allows trends to be identified. It is also possible, however, that trends are produced which are an artefact of the smoothing process.

Figure 9.6 shows the running mean of changes in soil-moisture content, soil-surface temperature and crystal length for a typical experiment. Cumulative data is shown in Figure 6.24. First, temperature and moisture content were regressed against changes in crystal length individually. The R^2 values of these equations are quite low (Table 9.1; Equations 9.7 and 9.8; Figures 9.7 and 9.8). This was expected for the equation including soil moisture, because, the moisture content was measured 1 cm below the soil surface, and there would probably have been a time lag before the effects of an increase or decrease in moisture content was noticed at the soil surface. To take this into account the length/moisture content analysis was repeated with the moisture content lagged, so that, for example, the change in moisture content measured at hour one of the experiment was regressed against the change in crystal length at hour two. Manual cross correlation in 10 minute intervals was used to show the effect of different time lags. The greatest level of explanation of crystal length was found to be a lag of 70 minutes, giving Equation 9.9 (Figures 9.9 and 9.10).

The running mean of the change in crystal length and change in moisture content lagged 70 minutes is shown in Figure 9.10 and the actual and predicted length (calculated from Equation 9.9) in Figures 9.11 and 9.12. (Predicted negative rates, which usually occur when soil-moisture content decreases, indicate that no growth (rather than melting) will occur. It is assumed that melting does not occur because the soil-surface temperature remains below 0°C throughout the experiment.) The correlation between actual and predicted changes in crystal length was 0.56 (significant at 95% confidence level). This relationship is highly non-linear, however, and all actual changes above 0.225 mm are under-predicted. The non-

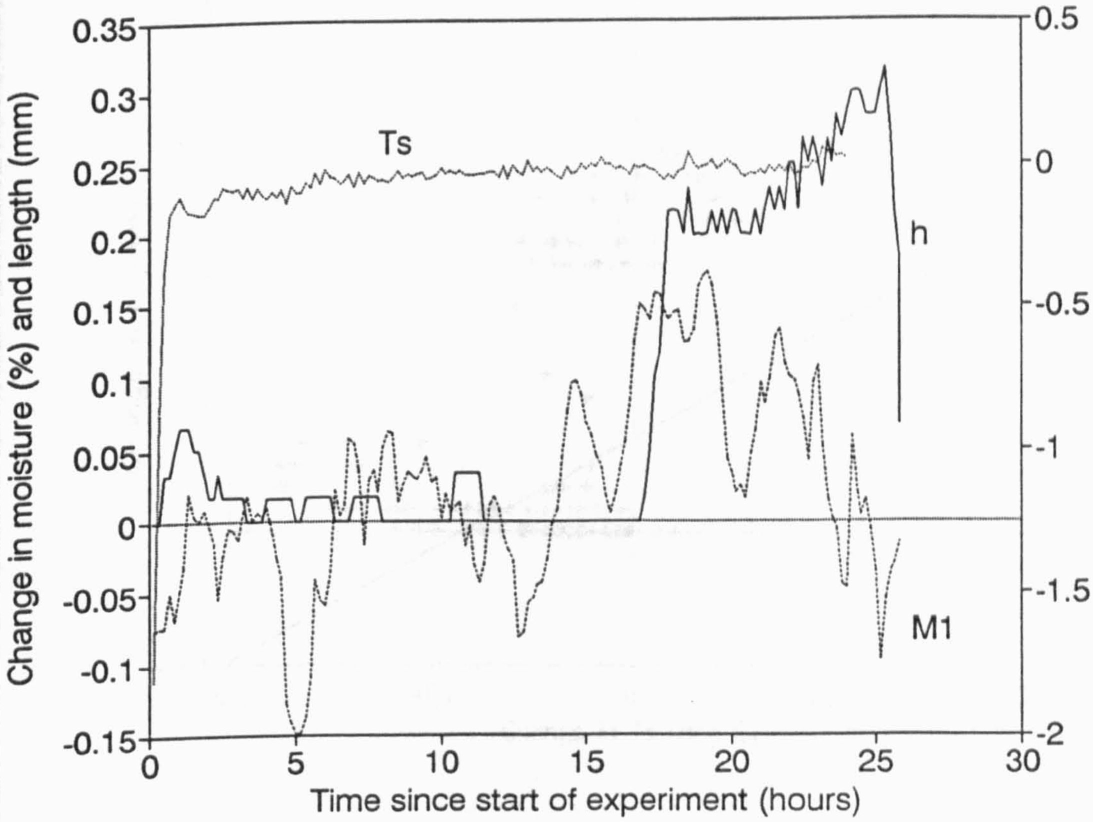

Figure 9.6 : Experiment 14/3/91, running mean of changes in soil-surface temperature, moisture content and crystal length **USB_1**

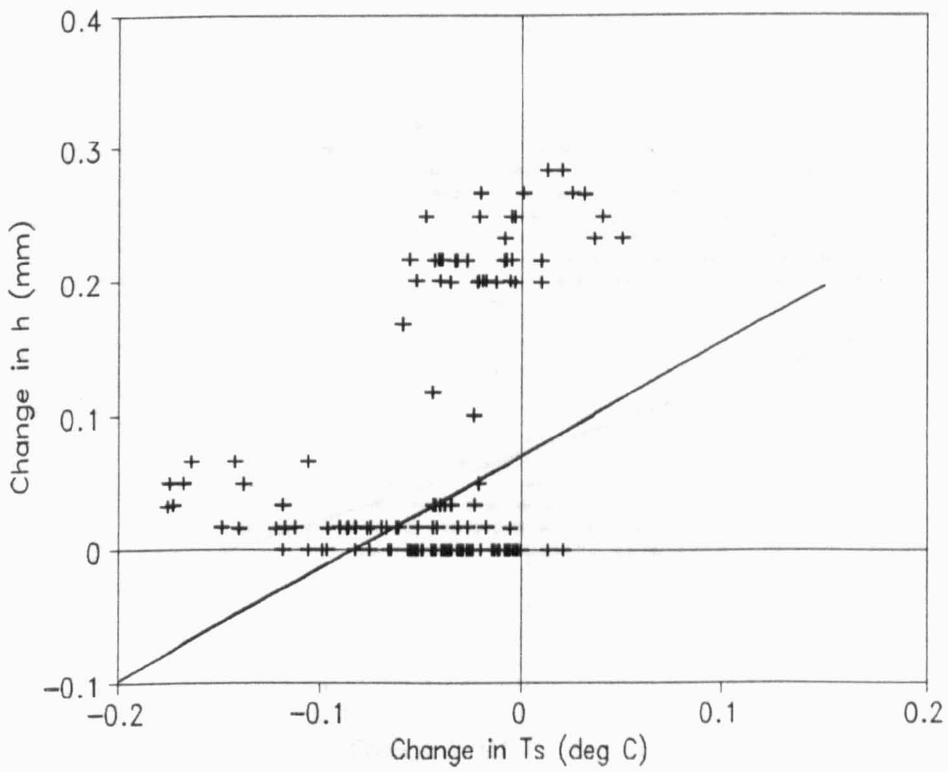

Figure 9.7 : Experiment 14/3/91, change in soil-surface temperature and crystal length
USB_1

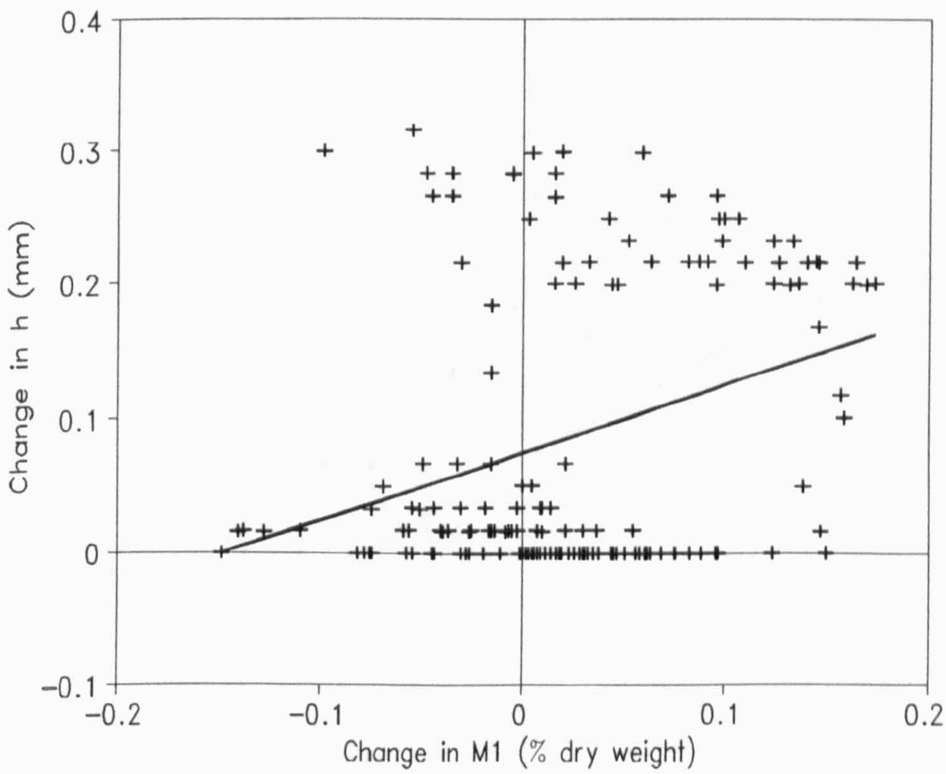

Figure 9.8 : Experiment 14/3/91; change in soil-moisture content and crystal length **USB_1**

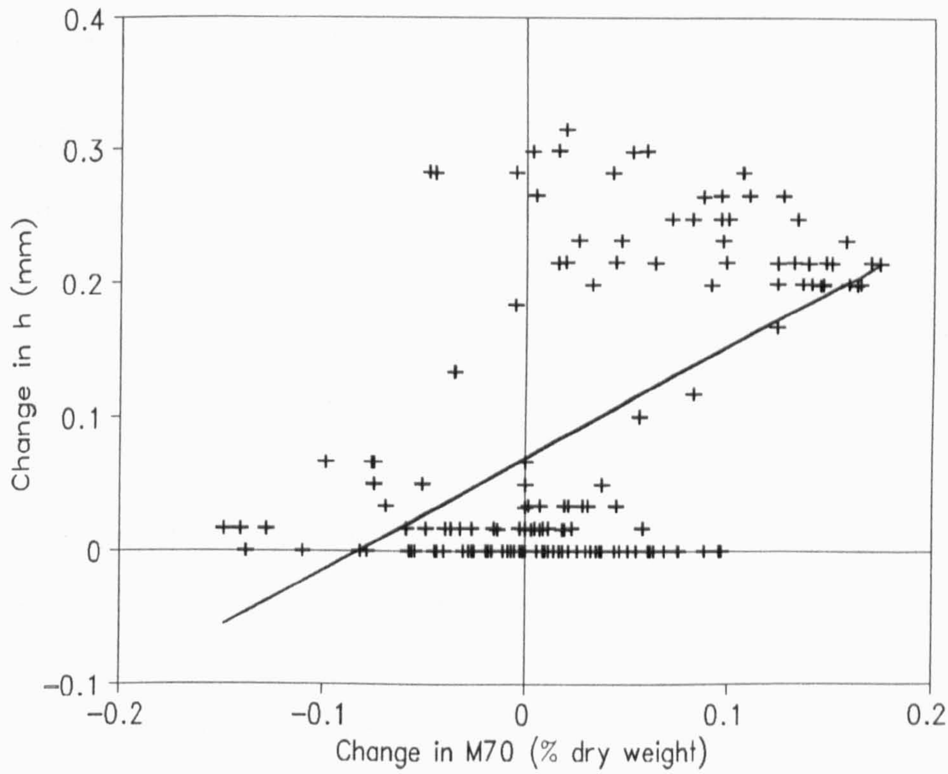

Figure 9.9 : Experiment 14/3/91; change in moisture content lagged by 70 minutes and change in crystal length USB_1

Table 9.1 : Equations to predict the rate of change of crystal length during a freezing cycle (Experiment 14/3/91)

Figure no.	Equation no.	Equation	R^2 (%)		St.error h-est. (mm)
9.7	9.7	$\Delta h = 0.07 + 0.10\ \Delta T_s$	3		0.10
9.8	9.8	$\Delta h = 0.074 + 1.02\ \Delta M$	11	*	0.10
9.9	9.9	$\Delta h = 0.07 + 0.83\ \Delta M_{70}$	29	*	0.08
	9.10	$\Delta h = 0.06 + 0.28 \Delta T_s + 0.88\ \Delta M_{70}$	48	*	0.07

*significant at 95% confidence level (n = 157)

ΔM_{70} represents the change in moisture content lagged by 70 minutes

linearity probably occurs because temperature is not included in the analysis. On some occasions during the freezing cycle it appears that decreases in temperature cause an increase in needle-ice height, providing that there was moisture available, even though there is no actual change in moisture content. Thus the actual rate of change increased whilst the predicted rate of change decreases.

In the early stages of the experiment the predicted changes in length are higher than the actual changes (Figure 9.11). The occurrence of peaks and troughs in growth are reasonably well predicted in the first eight hours of the experiment, although the magnitude of change was usually over-estimated. The rapid increase in length from hour 17 and the rate of growth from this time until hour 21 was reliably predicted. After this, the timing of the peaks was predicted, although the rate of change was under-estimated.

In the second stage of the analysis, when both moisture content and soil-surface temperature were used as independent variables, the R^2 value was increased, although the standard error of the h-estimate was only slightly reduced (Equation 9.10).

It is evident from the above that, in the analysis of growth rates of needle ice, it is necessary to include real-time changes in soil-surface temperature, and changes in soil-moisture

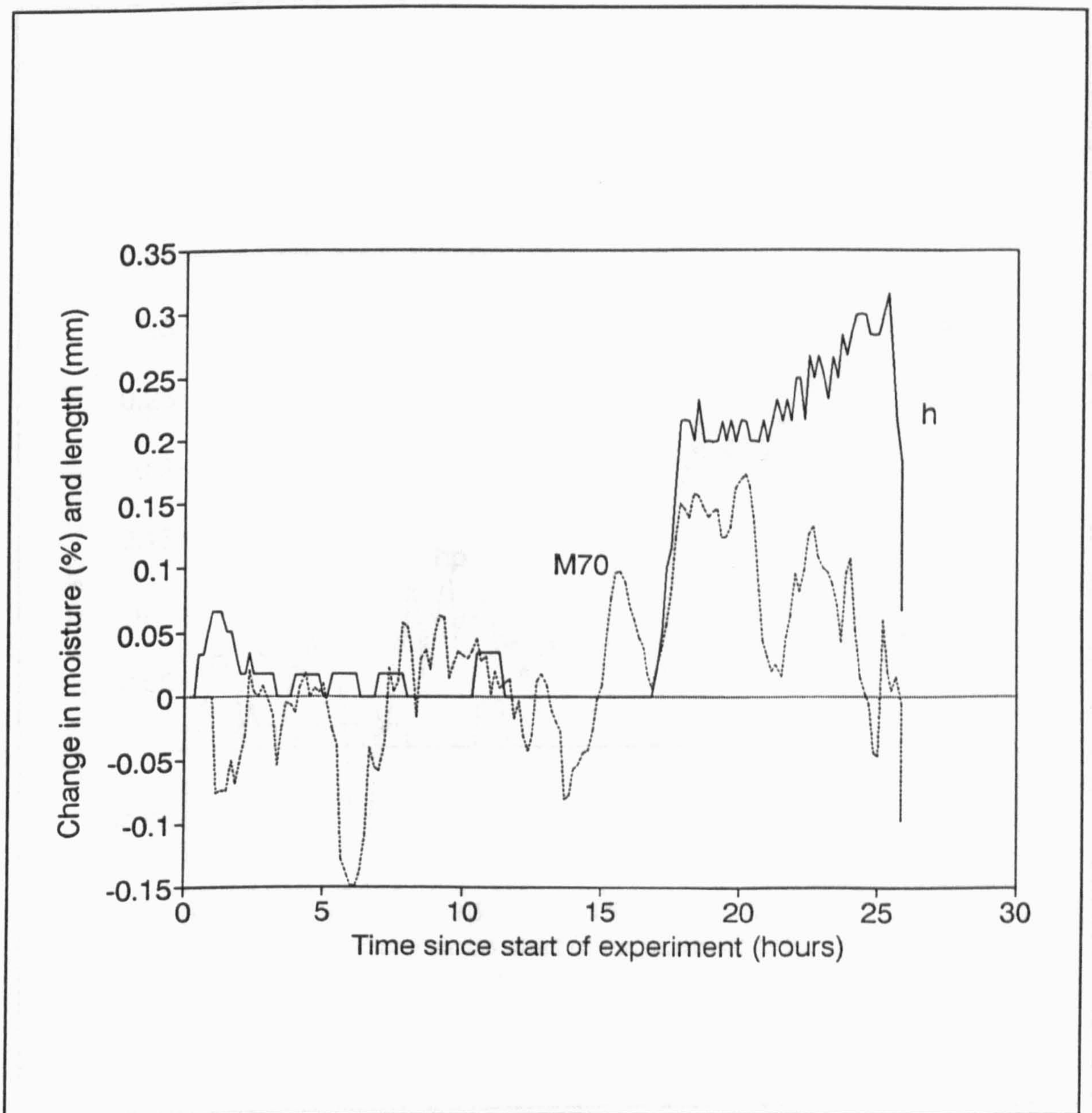

Figure 9.10 : Experiment 14/3/91; running means of changes in crystal length and moisture content (the latter lagged by 70 minutes) **USB$_1$**

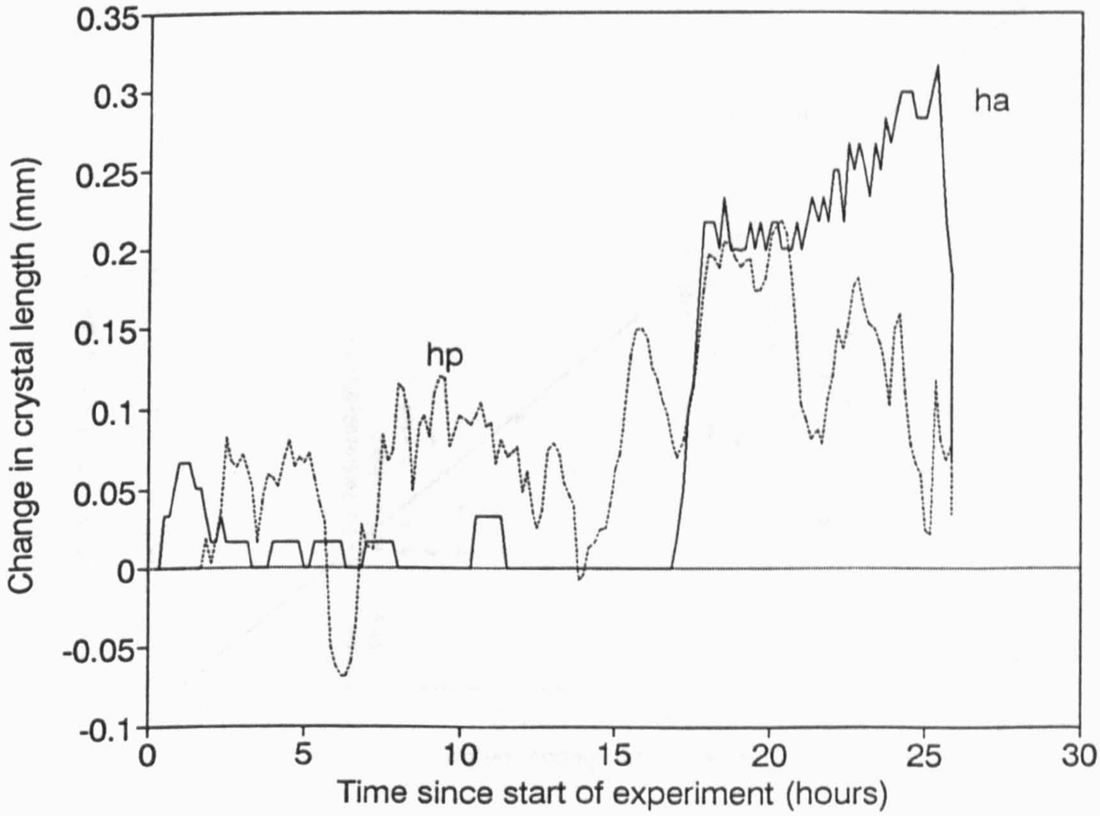

Figure 9.11 : Experiment 14/3/91; actual and predicted changes in crystal length USB$_1$

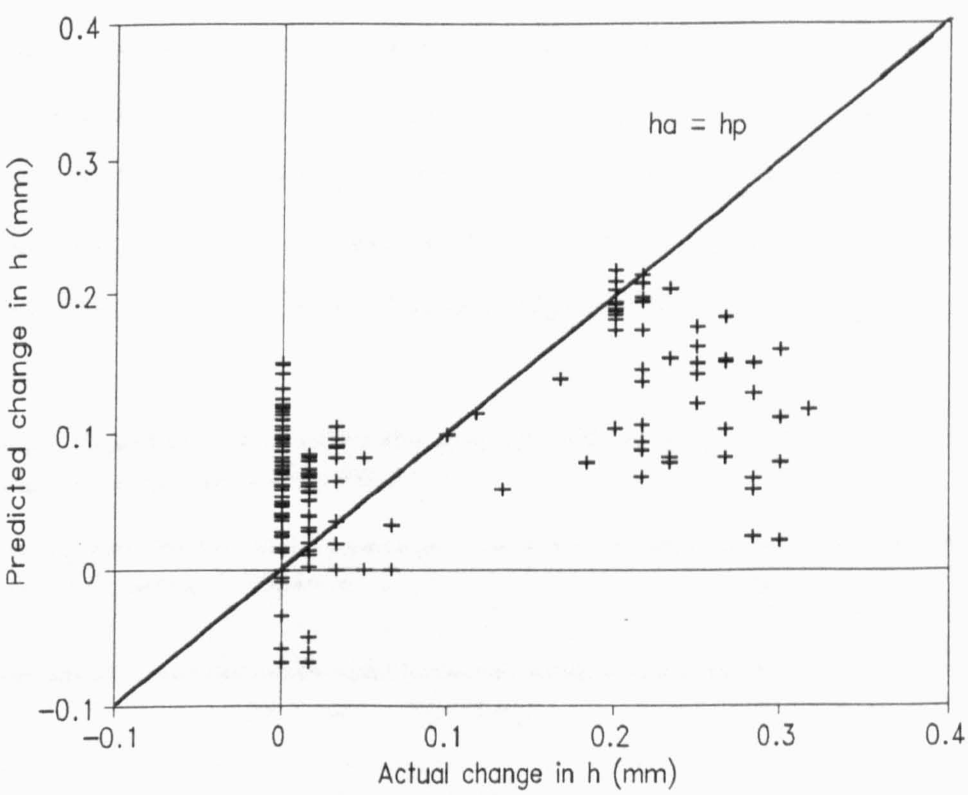

Figure 9.12 : Experiment 14/3/91; scatter plot of actual and predicted change in crystal length **USB_1**

content with a time-lag. The length of the time lag required will depend on the soil-surface temperature and, more importantly, on the moisture content at the start of the experiment. Soils with a relatively high moisture content, for example, have a high hydraulic conductivity (Chapter 2) and thus water will flow more quickly than in soils with a low moisture content. The lag between the effects of an increase in moisture flow on needle-ice growth is less in wet soils than for dry soils.

For Experiment 14/3/91, with an initial moisture content of 31%, there was a lag of 70 minutes at element M_1 before any changes in moisture content were reflected by changes in the rate of needle-ice growth at the soil surface (Figure 9.9). Another typical experiment (Experiment 30/1/91) (Figure 9.13), however, had a moisture content of 45% at the start of freezing and the lag between changes in moisture content and needle-ice growth was only 10 minutes (Figure 9.14 and 9.15). This gave Equation 9.11 (Table 9.2).

Table 9.2 : Equations to predict the change in length of needle-ice crystals during a freezing cycle (Experiment 30/1/91)

Figure no.	Equation no.	Equation	R_2 (%)		St.error h-est. (mm)
9.14 9.15	9.11	$\Delta h = 0.03 + 6.62\ \Delta M_{10}$	59	*	0.08
9.16	9.12	$\Delta h = 0.06 + 0.26\ \Delta T_s$	2		0.13
	9.13	$\Delta h = 0.04 + 0.36 \Delta T_s + 6.75\ \Delta M_{10}$	49	*	0.09

* indicates significant at 95% confidence level (n = 162)

ΔM_{10} represents the change in moisture content lagged by 10 minutes

The relationship between needle-ice growth and changes in soil-surface temperature was insignificant (Equation 9.12 and Figure 9.16). Adding the soil-surface temperature variable to the analysis (Equation 9.13) actually <u>reduced</u> the level of explanation of Equation 9.11 (Table 9.2). The actual and predicted changes in crystal length, based on Equation 9.11 are

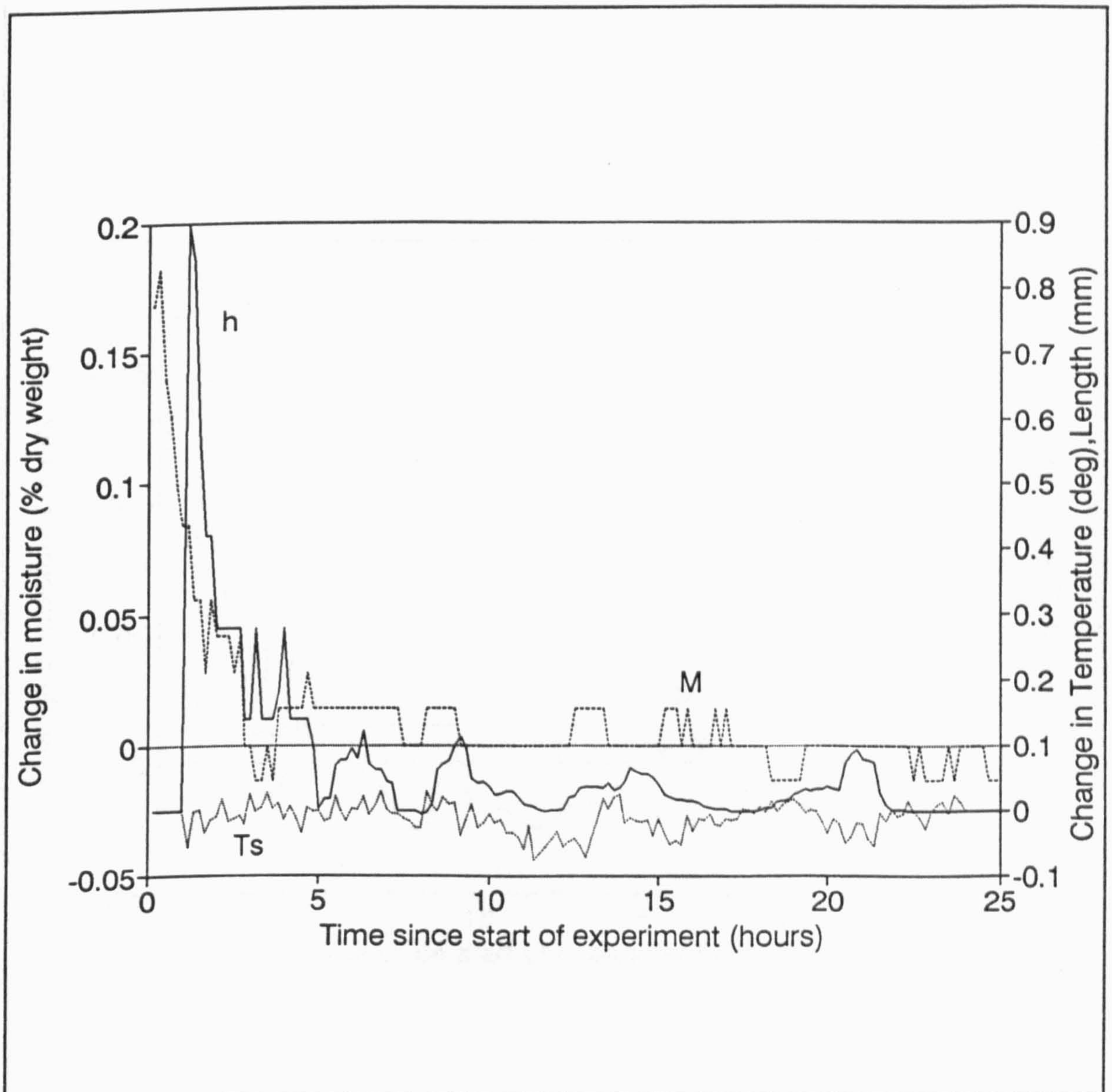

Figure 9.13 : Experiment 30/1/91; soil-moisture content, soil-surface moisture and crystal growth **USB_1**

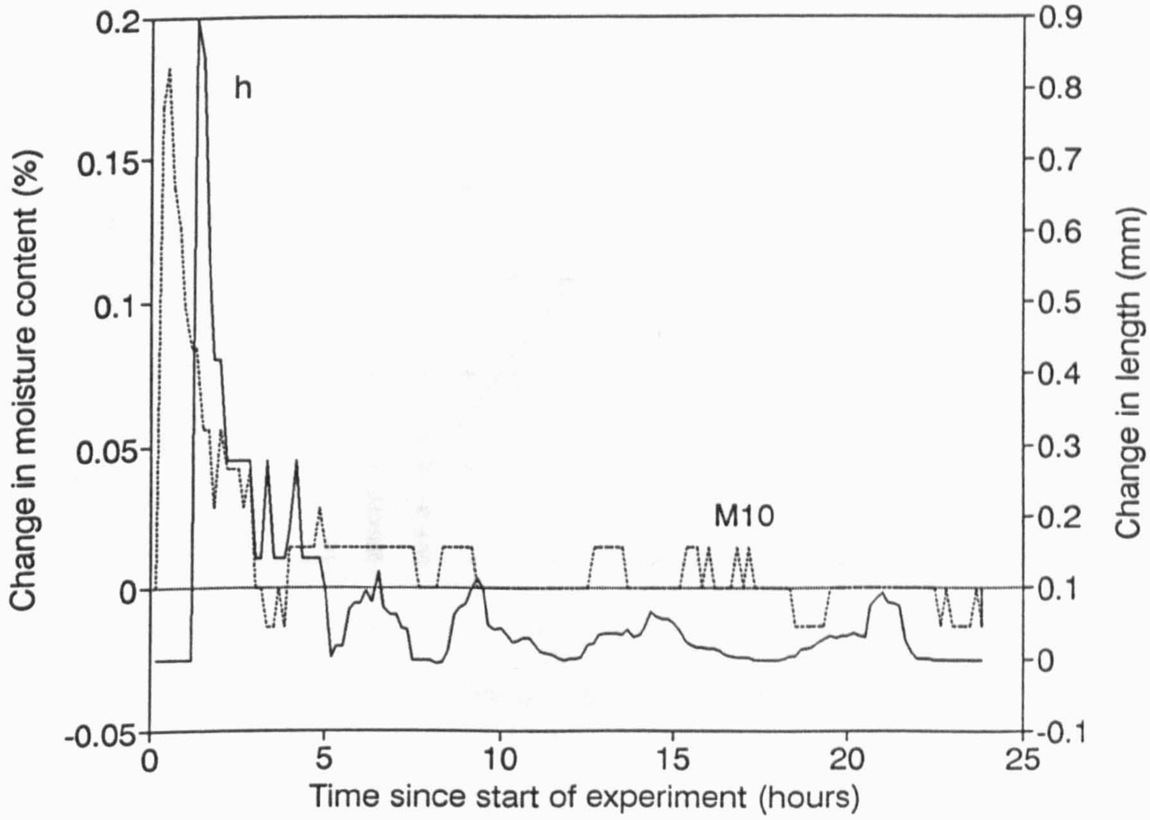

Figure 9.14 : Experiment 30/1/91; change in crystal length and moisture content (the latter lagged by 10 minutes) USB_1

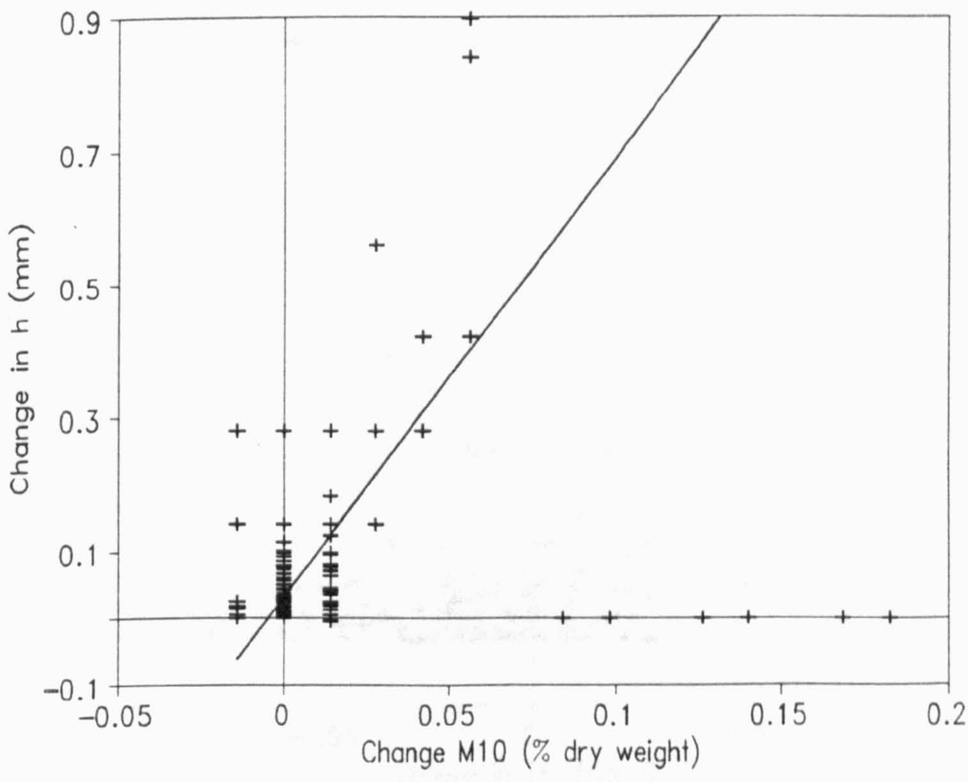

Figure 9.15 : Experiment 30/1/91; change in crystal length and moisture content (the latter lagged by 10 minutes) **USB_1**

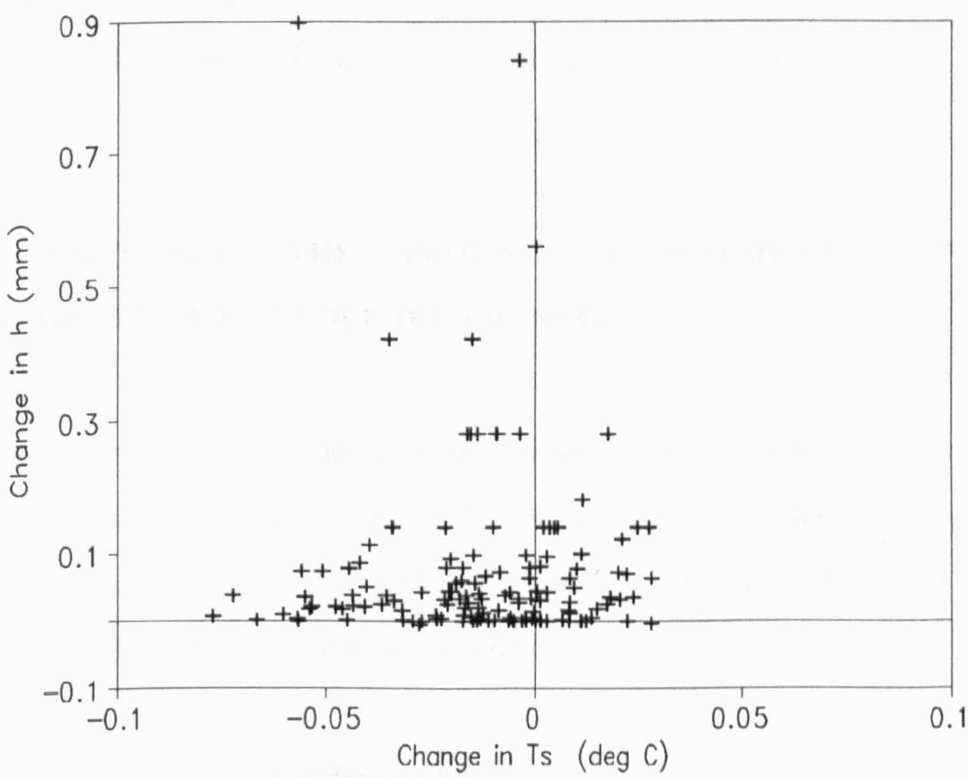

Figure 9.16 : Experiment 30/1/91; change in soil-surface temperature and crystal length USB$_1$

shown in Figure 9.17 and Figure 9.18. As with Figure 9.12 the relationship between actual and predicted lengths is non-linear, and changes in length over 0.4 mm are under-predicted. For this experiment the changes in crystal length are much higher than for Experiment 14/3/91. For Experiment 30/1/91 the maximum change in length is 0.89 mm (mean = 0.1 mm; minimum = 0 mm; standard deviation = 0.14 mm) and for Experiment 14/3/91 the maximum is 0.32 mm (mean = 0.1 mm; minimum = 0 mm; standard deviation = 0.14 mm). This difference between the experiments is probably a reflection of the high moisture content of the soil during Experiment 30/1/91 (the importance of soil-moisture content in controlling the length of needle-ice crystals was discussed in Section 6.2.4).

9.3 PREDICTING THE AMOUNT OF SEDIMENT LIFTED AND INCORPORATED BY NEEDLE-ICE CRYSTALS

Given the importance of needle ice as an agent of soil erosion in many areas (Chapters 1 and 3) it is important to be able to predict the amount of sediment that is incorporated and transported by needle ice. Such a model could provide a valuable addition to soil-erosion models which do not take account of frost effects.

9.3.1 A representation of sediment lift

Lawler (1987) produced an empirical power function, based on data from the River Ilston, South Wales, which related the amount of sediment incorporated by needle ice to the needle length

$$E-1.6h^{1.14} \qquad (9.14)$$

($n = 29$; $R^2 = 46.6\%$; significant at 99.9% confidence level),

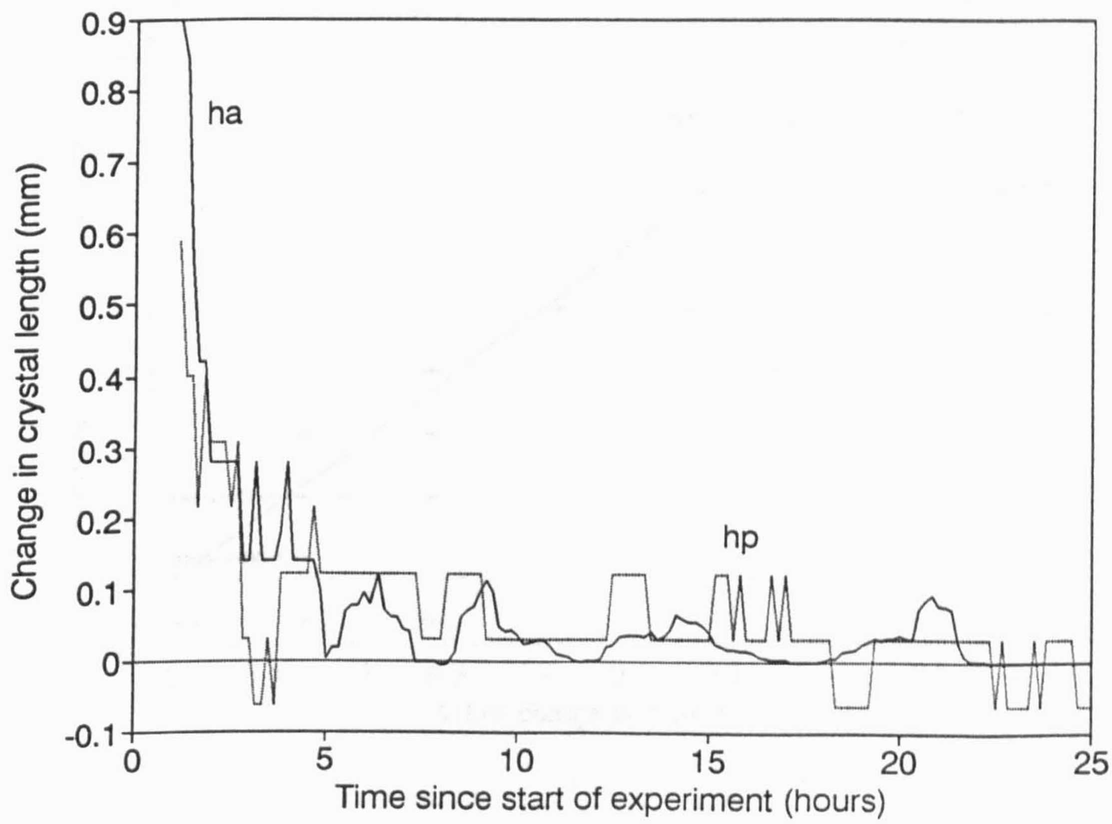

Figure 9.17 : Experiment 30/1/91; actual and predicted changes in needle-ice length **USB_1**

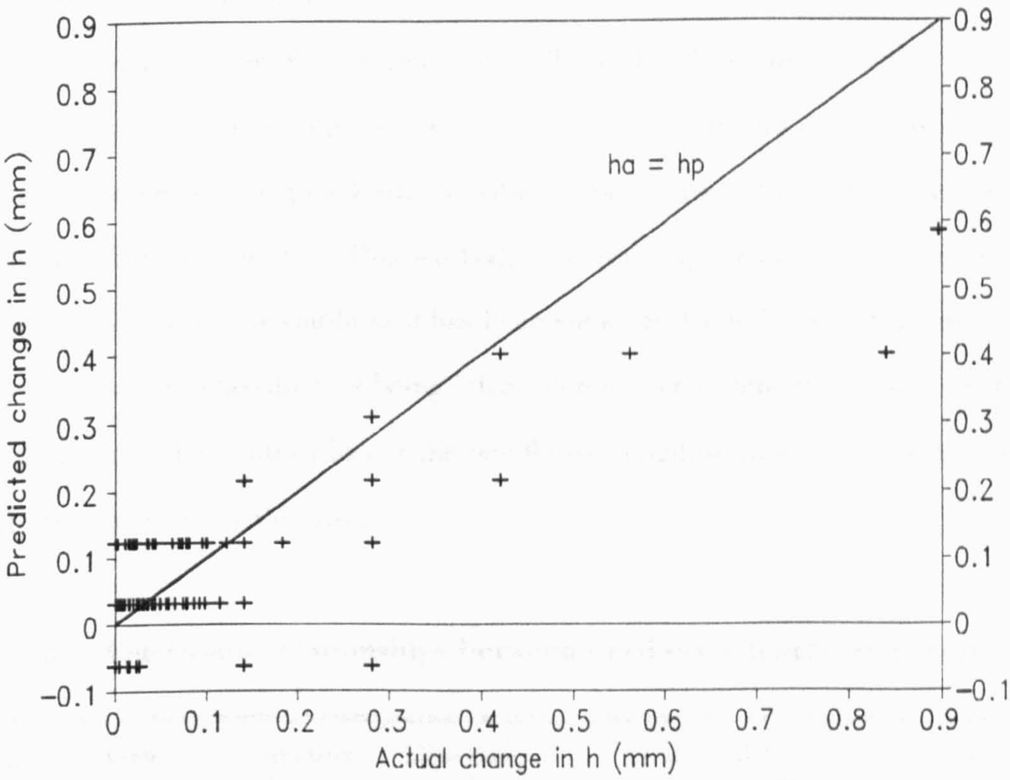

Figure 9.18 : Experiment 30/1/91; scatter plot of actual and predicted changes in crystal length **USB_1**

where E is the sediment yield or dry weight of sediment incorporated within the needle ice per unit area of soil surface (g cm^{-2}) and h is crystal height in mm.

Lawler argued that additional data were required to improve the significance of the relationship. He suggested that the total weight of uplifted sediment should also be linked to disturbances in the flow of water and heat to the freezing front.

Table 9.3 shows the relationships between needle-ice length and sediment yield calculated for the soil samples from the present study. To make these relationships realistic, the regression plots were forced through the origin, so that sediment erosion is not predicted when there is no needle-ice growth (the possible problems associated with origin forcing have been discussed in Section 8.1). This method, however, implies that all needle ice contains sediment, but is not unreasonable as it has been shown in Table 7.1 and Figures 7.2 and 7.3 that crystals that are classified as being 'clear' contain small amounts of sediment. Figures 9.19 to 9.22 show the scatter plots of the needle-ice length/sediment yield relationships for the soil samples used in this study.

Table 9.3 : Regression relationships between needle-ice length and sediment yield

Sample	Figure no.	Equation no.	Equation	n	R^2 (%)		St. error E-est. (g cm^{-2})
All	9.19	9.15	$E = 0.03\ h$	167	18.9	*	0.47
DSE_1	9.20	9.16	$E = 0.02\ h$	66	76.2	*	0.45
USB_1	9.21	9.17	$E = 0.04\ h$	88	12.4	*	0.39
Field	9.22	9.18	$E = 0.03\ h$	13	7.0		0.31

* indicates significant at the 95% confidence level

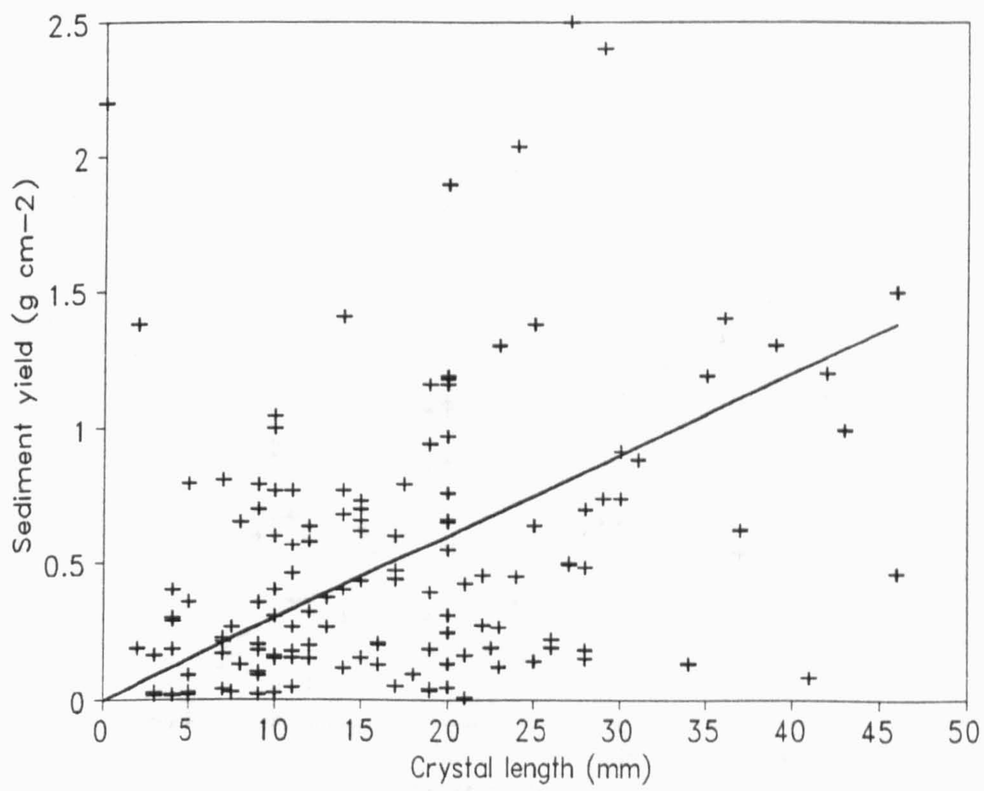

Figure 9.19 : All soil samples; needle-ice length and sediment yield

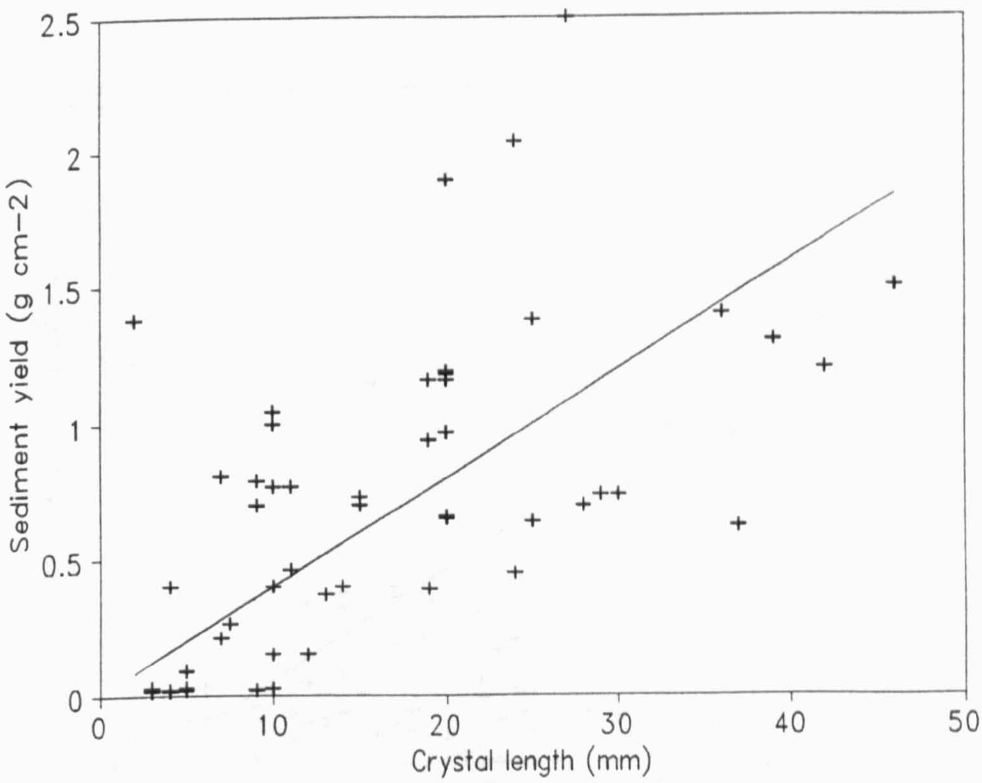

Figure 9.20 : DSE_1; needle-ice length and sediment yield

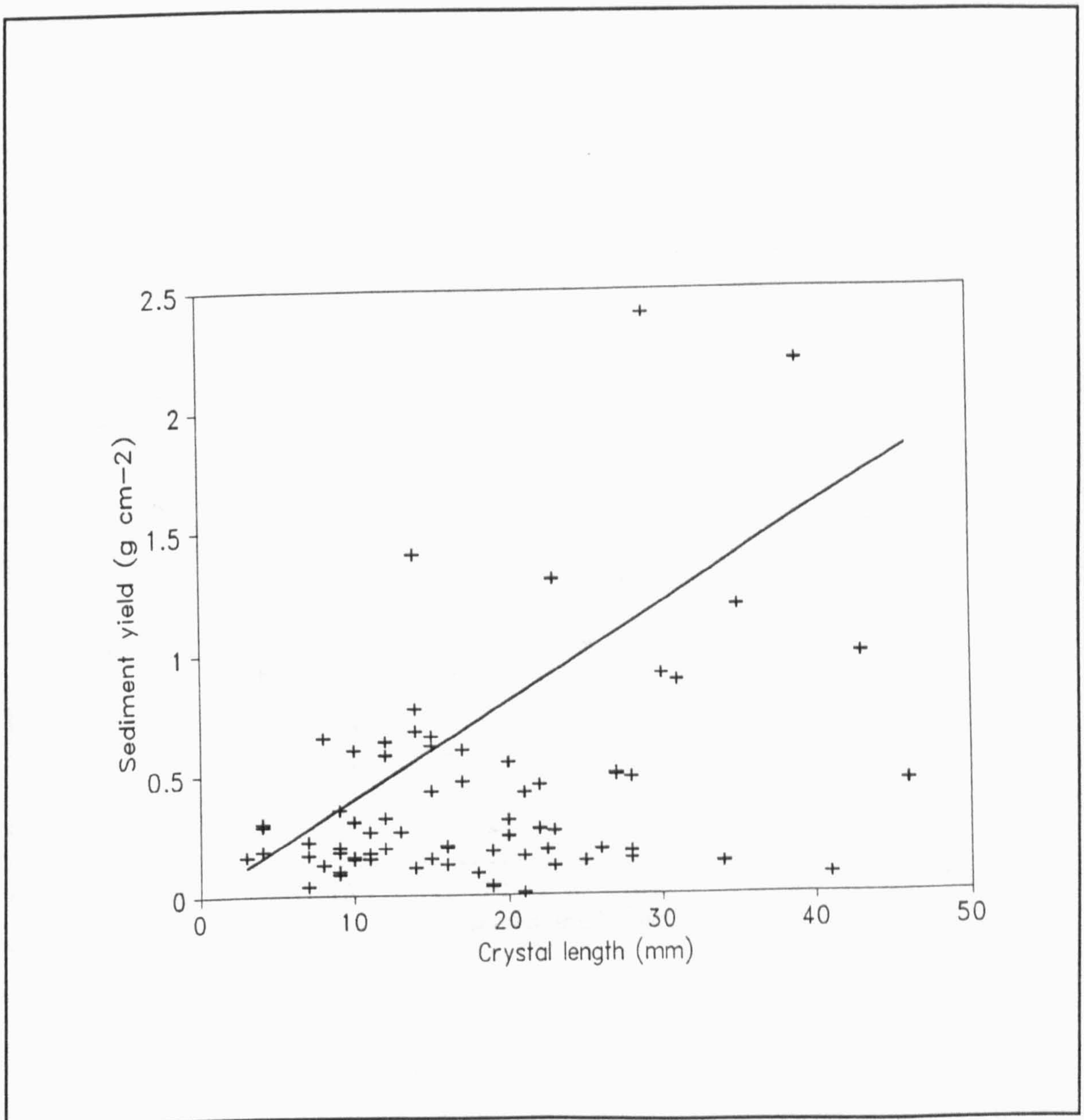

Figure 9.21 : USB_1; needle-ice length and sediment yield

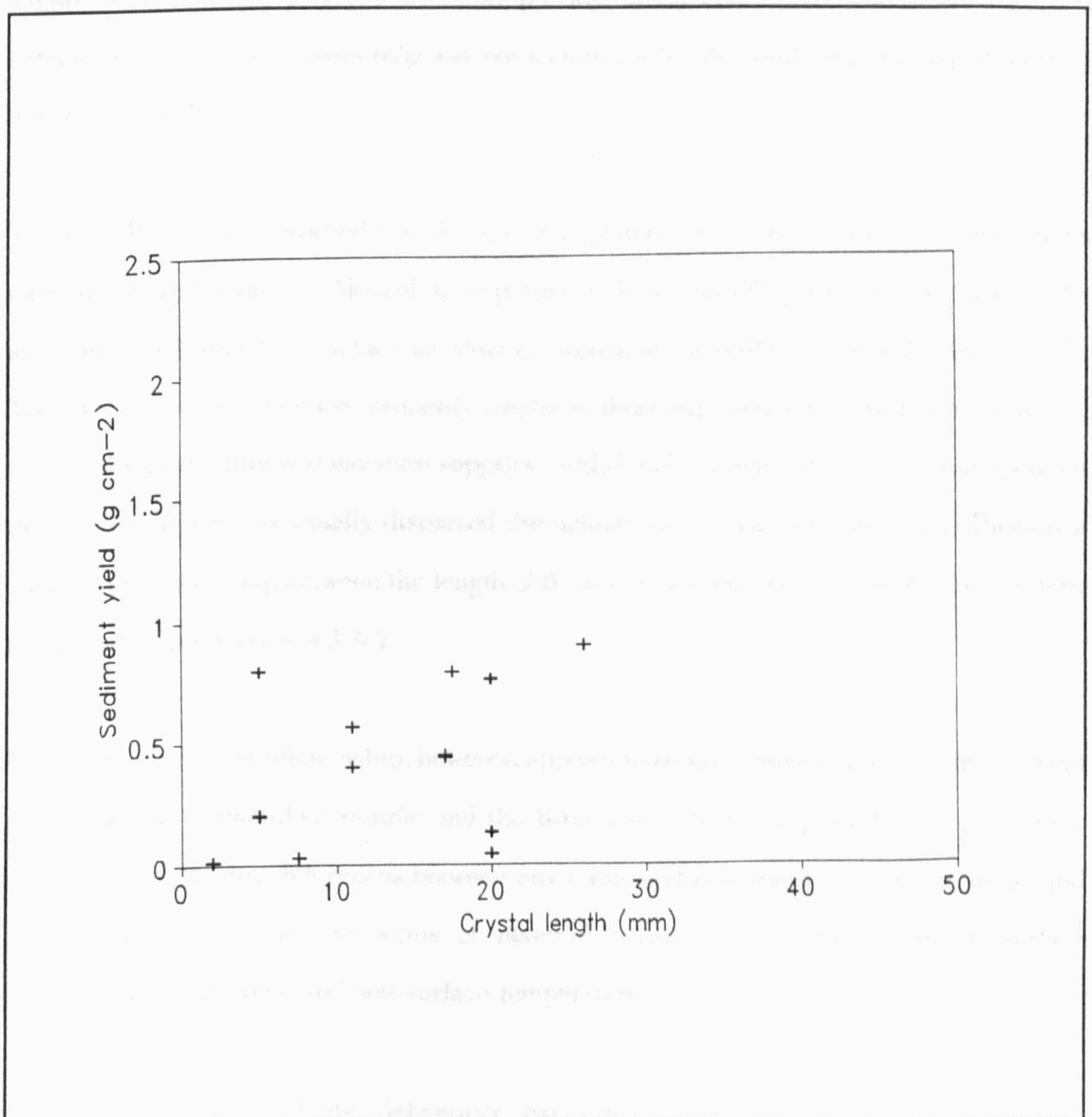

Figure 9.22 : Birmingham field samples; needle-ice length and sediment yield

The relationship for all the soil samples investigated together is significant (Equation 9.15). When the data set was broken down into 3 categories, however, significant differences emerged. The relationship between crystal length and sediment yield was significant for the disturbed (Equation 9.16 and Figure 9.20) and undisturbed samples (Equation 9.17 and Figure 9.21). The R^2 of undisturbed sample was much lower than that of the disturbed sample, however. The relationship was not significant for the field samples (Equation 9.18 and Figure 9.22).

The high R^2 for the disturbed sample may be explained by the nature of the investigations carried out on that sample. Most of the experiments based on DSE_1 were designed to test the apparatus, and aimed to produce an ideal environment for needle-ice growth (Section 5.2). The conditions were therefore probably similar to those experienced at the River Ilston, i.e. slow cooling and unlimited moisture supplies. Additionally, when sediment was incorporated into the needles it was usually dispersed throughout the crystal (Section 7.3.2). There is a significant relationship between the length of these crystals and the amount of sediment they incorporate (see Section 9.3.3c).

The form of the Ilston relationship, however, appears to be unsuitable to predict the sediment yield from the undisturbed sample and the Birmingham field samples. This is probably a result of the following differences between environmental conditions in these locations and those at the Ilston site, in terms of material texture, soil-moisture content, surface desiccation, needle type and soil-surface temperature:

i) in some of the laboratory experiments disturbances were intentionally introduced into the growth environment (Sections 5.3.2 and 7.3). These disturbances often caused ice segregation to cease and sediment to be incorporated (Chapter 7). A long crystal, however, which according to Equation 9.14 is expected to yield a greater amount of sediment, usually indicates that the conditions for ice segregation have been fulfilled for long periods. Thus, only a small amount of sediment will have been incorporated into the crystal. A shorter ice crystal with dispersed sediment will therefore have a larger sediment yield than a longer clear crystal (compare Figures 9.27 and 9.28 with Figure 9.30, for example);

ii) the soil surface was often desiccated (by the heat lamp in the laboratory, or by evaporation at the field site). This commonly caused the minimum soil-moisture content for needle-ice growth to be below the soil surface (Section 7.3.3). Thus a soil cap was often lifted by the ice needles. For equivalent lengths of ice crystal those with a soil cap yielded a much larger amount of sediment than those without a cap (Table 7.1 and Figure 7.2). At the River Ilston location and on DSE, however, soil caps were not reported, probably because of the perennially wet conditions;

iii) at the Birmingham field sites, the time lapsed since the last rainfall event in relation to the occurrence of freeze-thaw events controlled the amount of sediment incorporated. For example, from 10 to 15 January 1991 needle ice grew every evening at Site 1 (a garden), during which time there was no rainfall. The crystals became dirtier and shorter over successive nights. At the River Ilston the soil moisture supply was probably not limited (Section 9.2);

iv) different types of needle ice contained different amounts of sediment for an equivalent length of crystal (Table 7.1, Figure 7.2 and Section 9.3.3).

9.3.2 Improving the prediction of sediment yield for the laboratory study

In the light of Lawler's suggestions (discussed in Section 9.3.1), the analysis in Chapters 6 and 7, and the observations made above, a new semi-empirical model of sediment transport has been developed. Soil-moisture and temperature variables were included in the analysis as well as needle-ice length, as they are known to affect the incorporation of sediment into needle ice (Chapter 7).

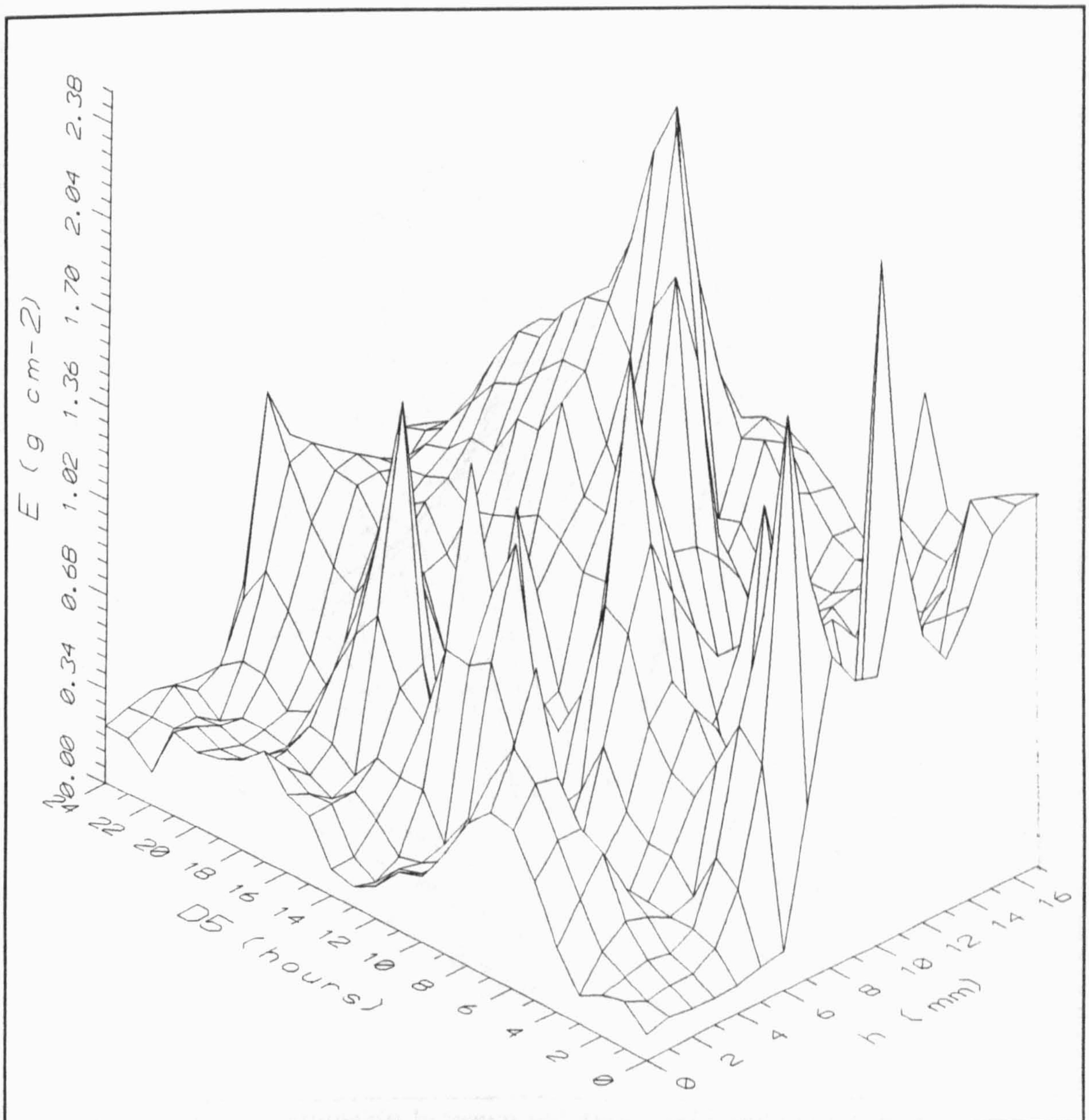

Figure 9.23 : The relationship between sediment yield and crystal length and D_5

In Chapter 7 it was shown that when the temperature falls below a certain threshold, ice segregation ceases, and sediment inclusion occurs. The time that soil-surface temperature was below -5°C (D_5) was used to represent the role of temperature in sediment incorporation. Whilst D_5 had a negative effect on the length of needle-ice crystals in Equation 9.3, in the sediment equation it has a positive effect (i.e. the longer that temperature is below the critical threshold the more sediment is incorporated). Soil moisture was represented by the moisture content at the soil surface at the start of freezing. This was expected to have a negative influence on sediment yield, as the lower the soil-moisture content the more likely that sediment would be lifted or incorporated (Chapter 7). Needle-ice length was also included in the equation, giving

$$E=ah-bM_s+cD_5 \tag{9.19}$$

where a, b and c are constants.

When this model was applied to all the data it gave the following (shown in Figures 9.23 and 9.24)

$$E=0.047h-0.007M_s+0.024D_5 \tag{9.20}$$

(n= 93; R^2 = 42%; St.error E-est. = 0.44 g cm^{-2}; significant at 95% confidence level).

This form of equation doubled the R^2 value of the E-prediction. The standard error of the E-prediction has not been improved greatly, however; this is probably because different types of needles, and thus amounts of sediment incorporation, are formed as a result of different processes. For example, the formation of soil caps is primarily caused by low soil-moisture contents at the soil surface prior to ice nucleation, and thus the amount of sediment uplift will not be related to the soil-surface temperature or needle-ice length, whilst the production of needles with dispersed sediment, is influenced by soil-surface temperature and moisture content during the freezing cycle. The largest residuals produced from Equation 9.20 were

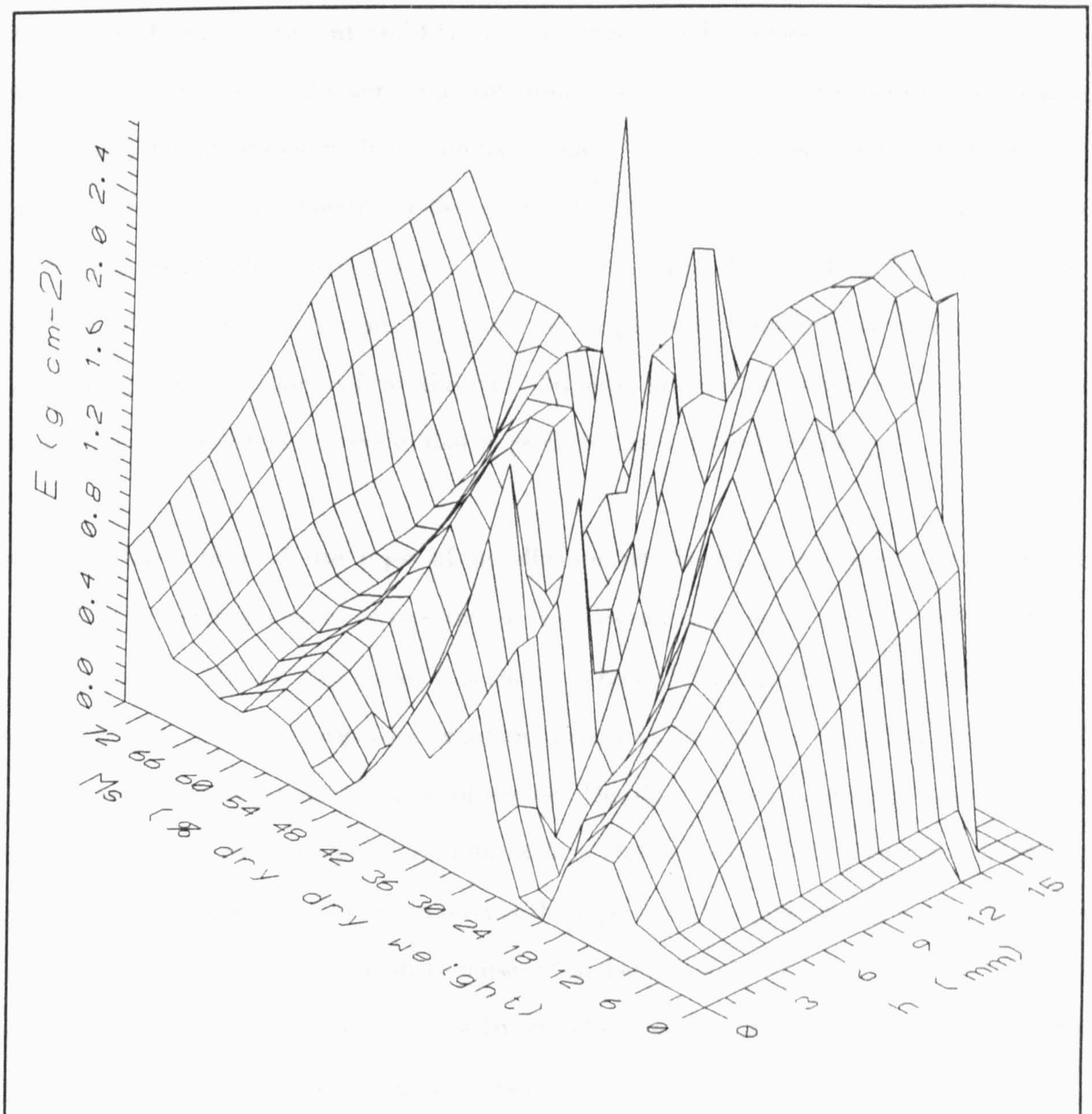

Figure 9.24 : The relationship between sediment yield and crystal length and soil-moisture content

for the long clear crystals and crystals that lifted aggregates of sediment (the production of aggregates is controlled by grain-size composition rather than moisture and temperature conditions (Section 7.3.4)).

9.3.3 Predicting sediment yield from individual needle types

It was demonstrated in Chapter 7 that different types of sediment incorporation occur as a result of different processes. It is therefore evident that it is not appropriate to attempt to predict the yield from different needles in one equation. In the light of this, and the analysis in Section 9.3.2, the needles were split into the types discussed in Section 7.3, i.e. multitiered, dispersed sediment, soil caps and aggregates. Later in this section, separate models are presented for each needle type. Initially, however, a model is discussed which aims to predict the type of needle that is produced in a given freezing cycle.

9.3.3a Prediction of the type of needle-ice produced. If sediment yield is to be predicted in terms of needle-ice type then it is necessary to know the type of needle that was produced during the freezing cycle. This can be achieved either by direct observation, in the laboratory or field, of the proportion of different needle types, or with the use of moisture and temperature data to predict the type of needle. The first method is preferred, but may not always be possible. Thus, an algorithm in the style of Outcalt (1971a and Figure 3.4) has been developed by which it is possible to predict the type of needle produced (Figure 9.25). The algorithm differs to that of Outcalt because it has been quantified to take into account the moisture and temperature threshold conditions which cause different types of needles to be formed, and thus is specific to the soils used in this study.

The main problem with the algorithm as presented in Figure 9.25 is that it cannot predict the formation of sediment aggregates. This is because it is difficult to assess, and then represent, the specific conditions under which aggregates are lifted. This is unfortunate given

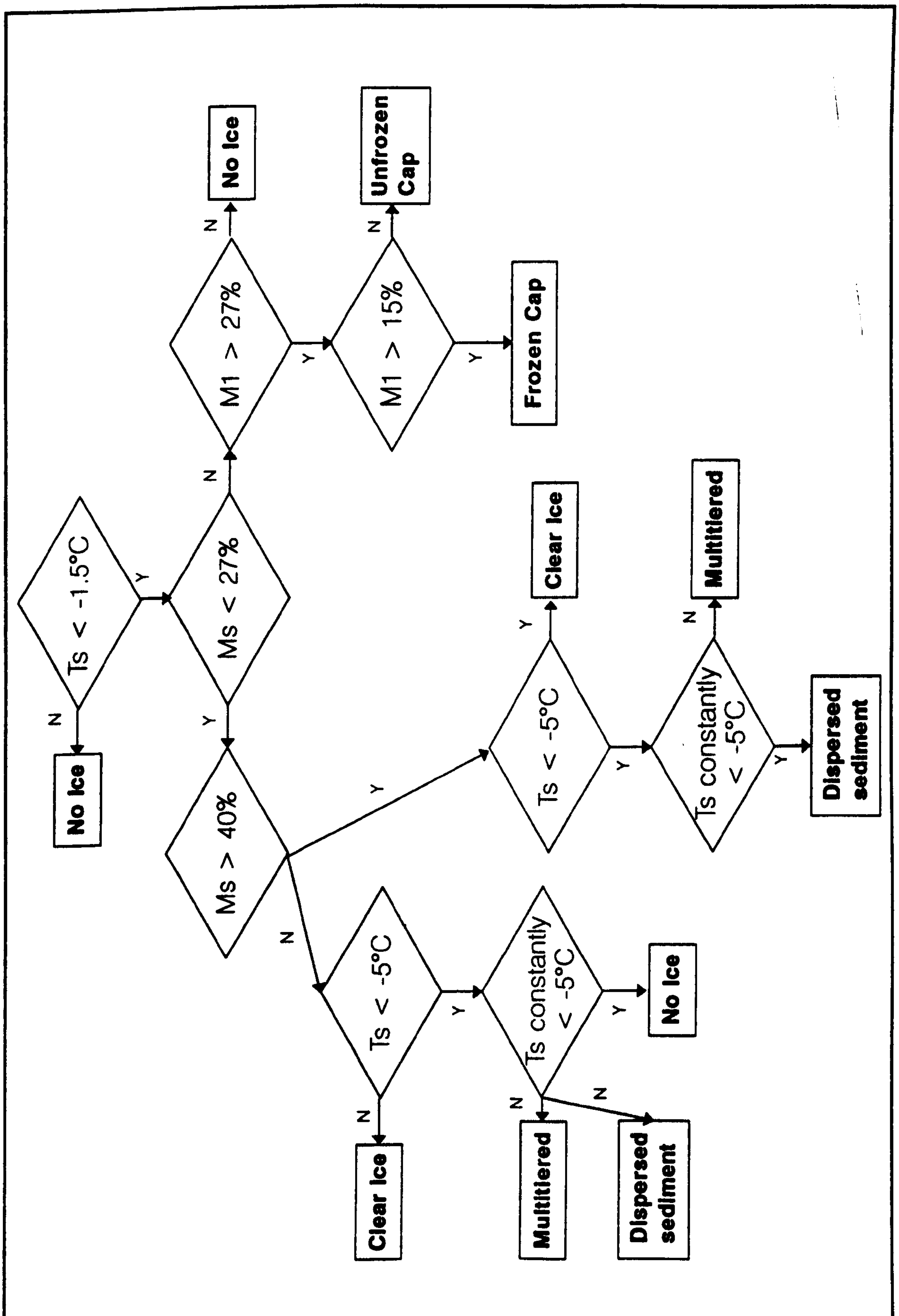

Figure 9.25 : An algorithm to predict the type of crystal that will grow in a given freezing cycle

the relatively large contribution of sediment aggregates to the total sediment yield (Table 7.1).

The algorithm was tested using the results from 150 of the laboratory experiments. The type of needle actually produced was compared with that predicted on the basis of temperature and moisture data using the algorithm; the results are shown in Table 9.4 and Figure 9.26. The data show that the algorithm was successful for predicting the needle type in 55.3% of the experiments.

Table 9.4 : Results from testing the needle ice type algorithm

	Actual (% of total experiments)						
Predicted (% of total)	**Multi**	**Dispersed**	**Cap**	**Clear**	**Aggregate**	**None**	**Total**
Multi	13.33	4.67	0.00	0.67	0.30	2.00	20.97
Dispersed	3.00	14.00	1.00	1.33	3.30	2.00	24.63
Cap	0.00	0.00	9.67	0.00	4.00	0.00	13.67
Clear	3.30	5.67	1.67	9.33	4.00	1.00	24.97
Aggregate	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
None	2.00	1.30	2.00	1.30	0.67	9.0	16.27
Total	21.63	25.64	14.34	12.63	12.27	14	100

correct predictions are shaded

The algorithm was most successful for predicting the development of clear needles and no needle ice and soil caps, where only one-third of experiments were put into the wrong category. For multitiered and dispersed-sediment crystals, half to two-thirds of the experiments which were predicted to produce these needle types were put into the wrong category. A large proportion of the incorrect predictions occurred when sediment aggregates were lifted.

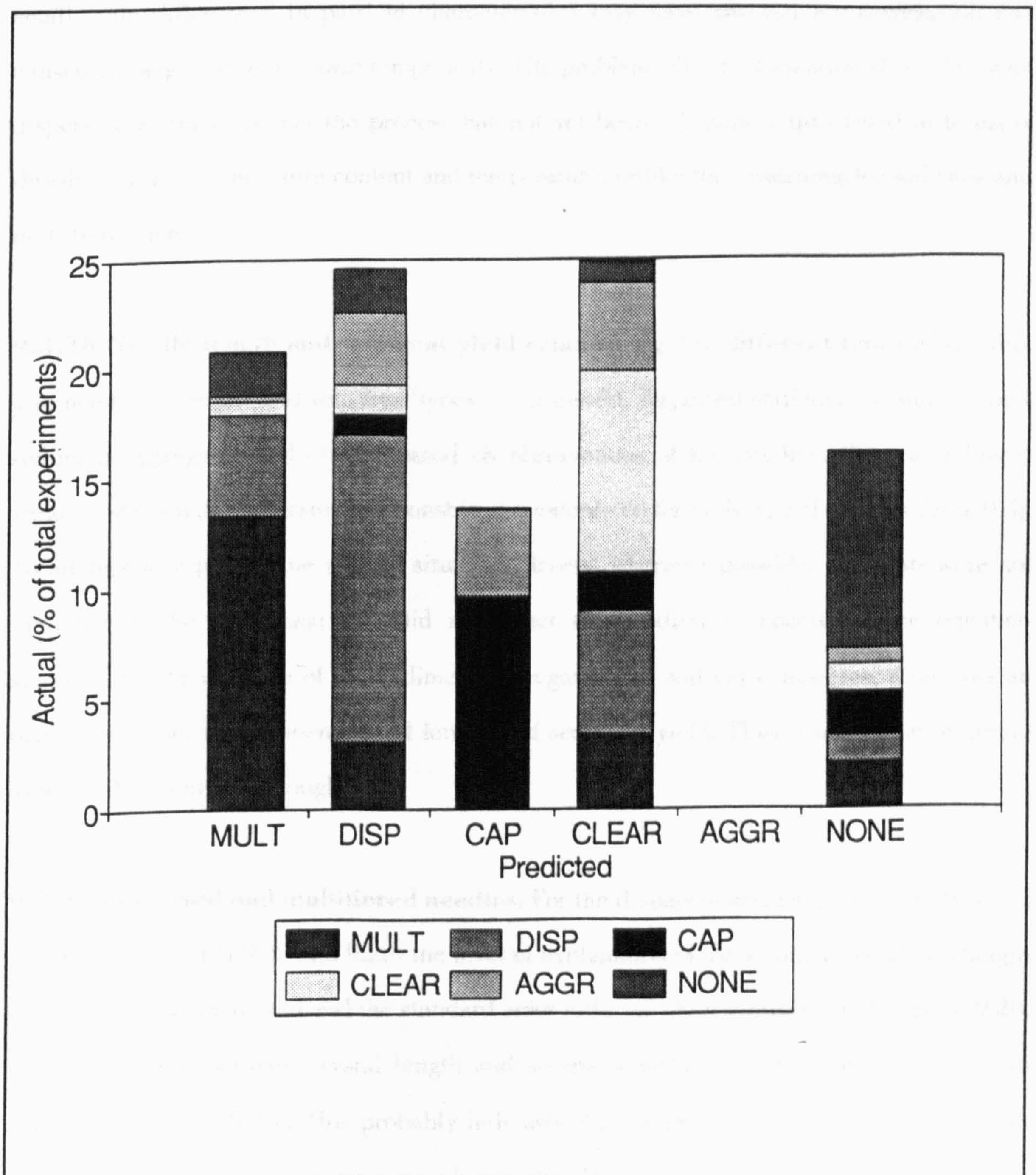

Figure 9.26 : Results from testing the needle ice type algorithm

The most common type of incorrect prediction occurred when clear needles were predicted but needles with dispersed sediment were produced. This usually occurred when the soil-moisture content was above 40%, and may indicate that either soil-surface temperature or small-scale differences in particle characteristics may have affected ice segregation and caused ice segregation to cease temporarily. The problem with the formation of needles with dispersed sediment is that the process has not yet been adequately quantified in terms of threshold values of moisture content and temperature, unlike the conditions for soil caps and multitiered ice.

9.3.3b Needle length and sediment yield relationship for different types of needle. The needles were divided into five 'types': multitiered, dispersed sediment, sediment caps, sediment aggregates and clear - based on observations of the needles. First, a sediment yield/crystal length regression relationship was calculated for each type of crystal (Table 9.5). To attempt to replicate the natural situation closely, wherever possible, constants were not included in the equations; this did not affect the predictive capacity of the equation significantly. In the case of the sediment aggregates and soil caps, however, there was an inverse relationship between crystal length and sediment yield. Thus it was not appropriate to force the equation through zero.

9.3.3c Dispersed and multitiered needles. For the dispersed and monocyclic multitiered ice needles (Figures 9.27 and 9.28) the level of explanation of the sediment yield and height relationship was increased and the standard error reduced when compared to Equation 9.20. The relationship between crystal length and sediment yield from the multitiered ice was curvilinear (Figure 9.28). This probably indicates that sediment is being incorporated with increasing efficiency during long growth periods. This may occur because as the crystals grow the supply of soil moisture is progressively reduced, thus there is a higher potential for sediment incorporation.

Table 9.5 : Matrix of simple regression between E and h for different types of needle ice

Type of crystal	Figure no.	Equation no.	Equation	n	R^2 (%)	St. error E-est. (g cm^{-2})
Dispersed	9.27	9.21	$E = 0.03\ h$	49	55.8 *	0.27
Multitiered	9.28	9.22	$E = 0.00008\ h^2$	45	36.4 *	0.37
Soil cap	9.29	9.23	$E = 0.48 + 0.002\ h$	24	15.0	0.43
Aggregates	9.30	9.24	$E = 1.26 + 0.01\ h$	24	1.0	0.79
Clear	9.31	9.25	$E = 0.003\ h$	25	2.6	0.06

* indicates significant at 95% confidence level

The equation for multitiered ice has a higher standard error than that for needles with dispersed sediment. This is probably because the sediment yield of multitiered ice will depend on the number of layers of sediment. In this section, multitiered crystals with one to five layers of sediment were analysed together, although 45% of the crystals had two layers.

9.3.3d Soil caps. The regression relationship between needle-ice length and sediment yield for soil caps was not significant (Equation 9.23 and Figure 9.29). The low h-coefficient of the regression equation indicates that the amount of sediment incorporated is independent of needle-ice length.

The standard error of the E-prediction for the soil caps was reduced when the moisture content at the soil surface was regressed against the sediment yield (Table 9.6 and Equation 9.26). There was an inverse relationship between the moisture content and sediment yield (Figure 9.32). It is expected that as the moisture content at the soil surface decreases the freezing front probably has to descend lower down in the soil profile to reach the moisture content sufficient for ice segregation. Thus, a greater amount of sediment is likely to be pushed up by the needles.

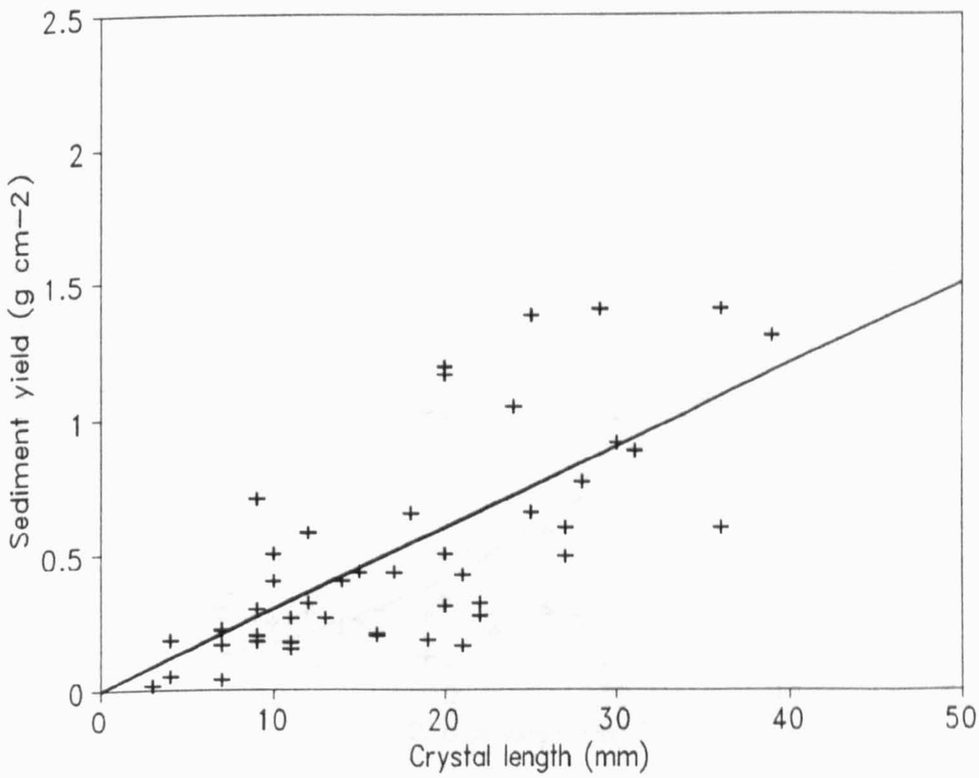

Figure 9.27 : Crystals with dispersed sediment; needle-ice length and sediment yield

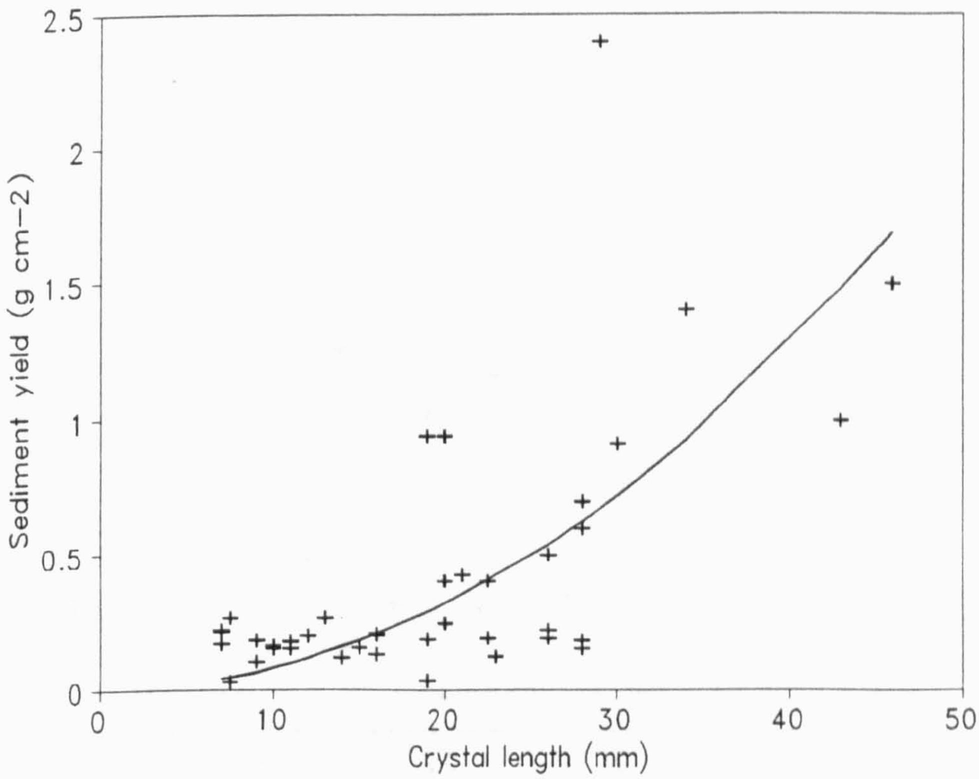

Figure 9.28 : Monocyclic multitiered needle-ice crystals; needle-ice length and sediment yield

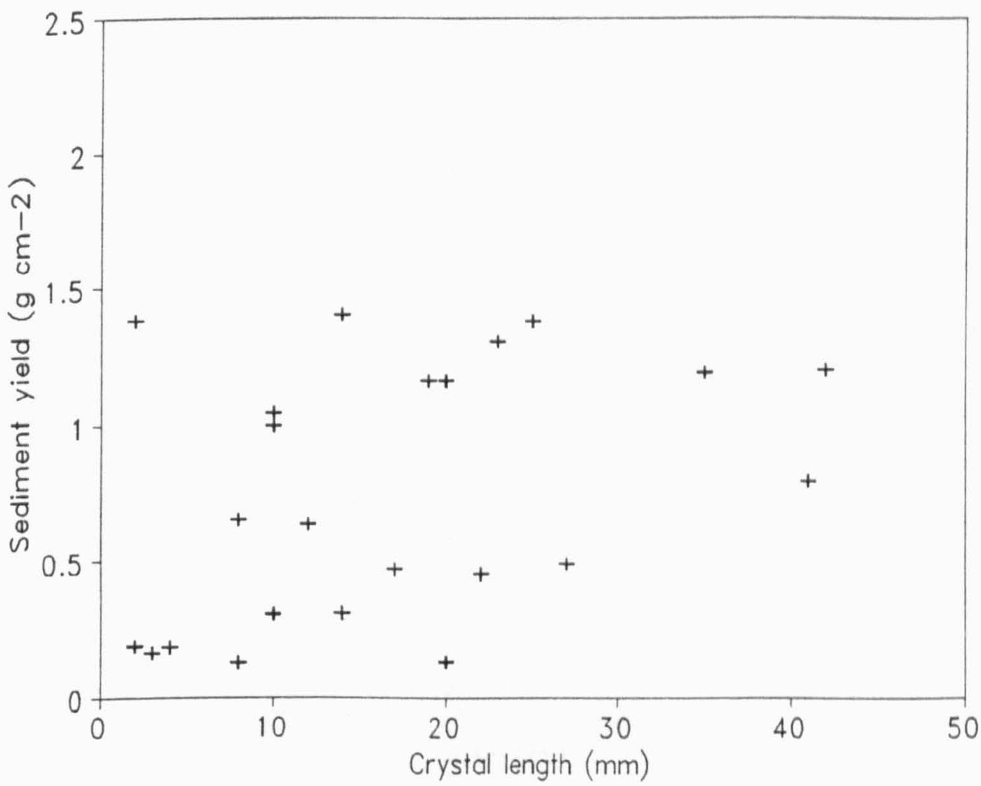

Figure 9.29 : Soil caps; needle-ice length and sediment yield

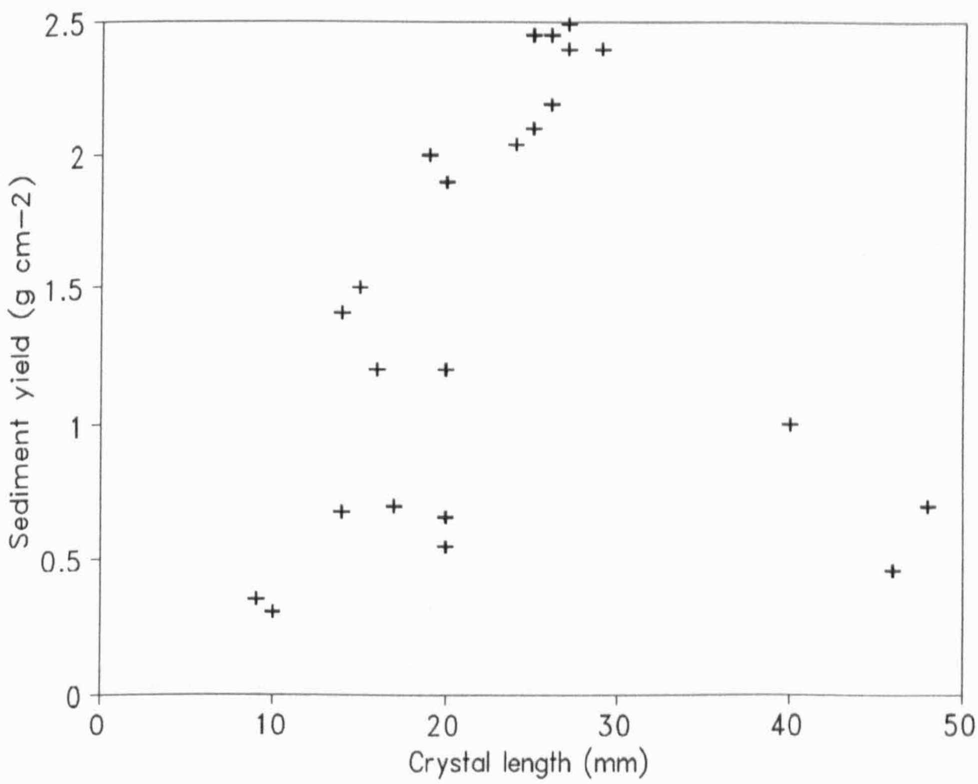

Figure 9.30 : Sediment aggregates; needle-ice length and sediment yield

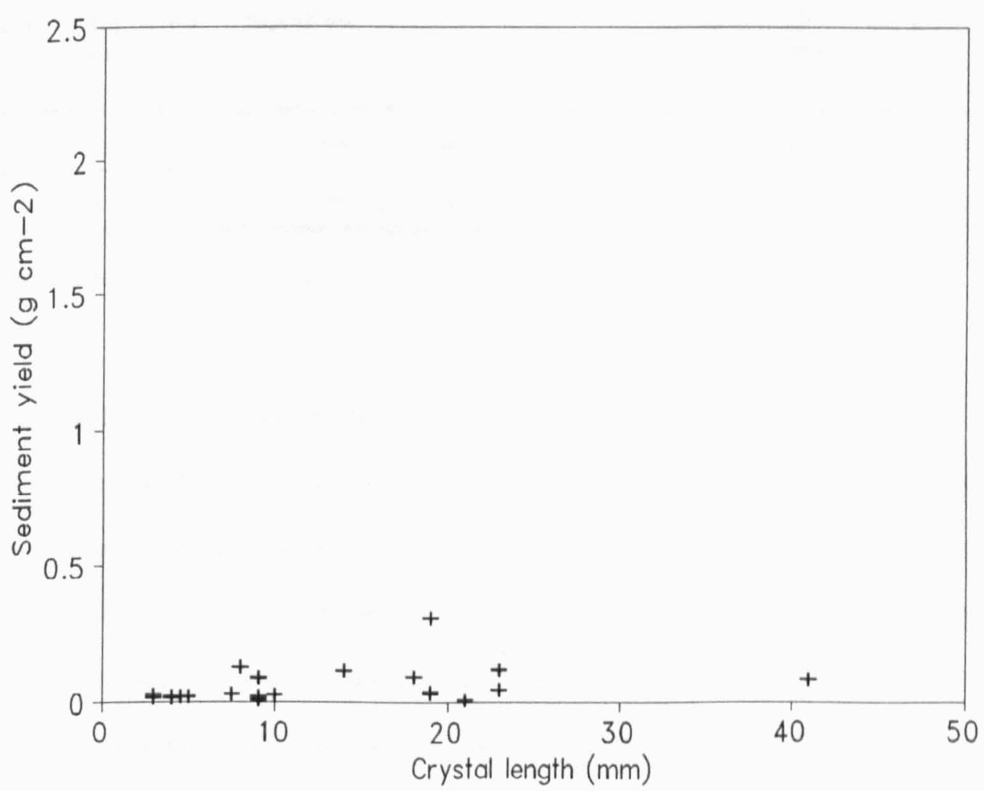

Figure 9.31 : Clear crystals; needle-ice length and sediment yield

The standard error of the E-estimate of Equation 9.26 was reduced when the length of needle-ice was included (Equation 9.27). This is probably because some sediment was included within the ice (as in crystals that contain dispersed sediment, which has been shown to have a significant relationship between sediment yield and crystal length, Equation 9.21).

Table 9.6 : Prediction of sediment yield for needle-ice crystals with soil caps

Figure no.	Equation no.	Equation	n	R^2 (%)	St. error E-est. ($g\ cm^{-2}$)
9.32	9.26	$E = 1.89 - 0.03\ M_s$	24	38	0.37
	9.27	$E = 1.89 - 0.03\ M_s + 0.01\ h$	24	43	0.36

both relationships significant at the 95% confidence level

A more suitable way of representing soil moisture would be to include details of the soil-moisture content within the top c.30 mm of the soil. In this way it should be possible, given soil temperature information, to determine where ice segregation will occur, and thus the height of the soil cap that will be uplifted. This will require the moisture content to be monitored with high vertical resolution which, was not possible in this study. Experiments which use time domain reflectometry methods to monitor soil moisture (e.g. Heimovara and Bouton, 1990) may be able to monitor soil moisture in much greater resolution, however.

9.3.3e Sediment aggregates. The length/sediment yield relationship was not significant for the sediment aggregates (Equation 9.24 and Figure 9.30). The E-prediction was improved, however, when the density of ice on the soil surface was related to sediment yield. There was a weak inverse relationship between the density of ice and the sediment yield (Figure 9.33). This is probably because if the density of cover is low then there is a greater potential for sediment to be uplifted from the areas in which there was no ice.

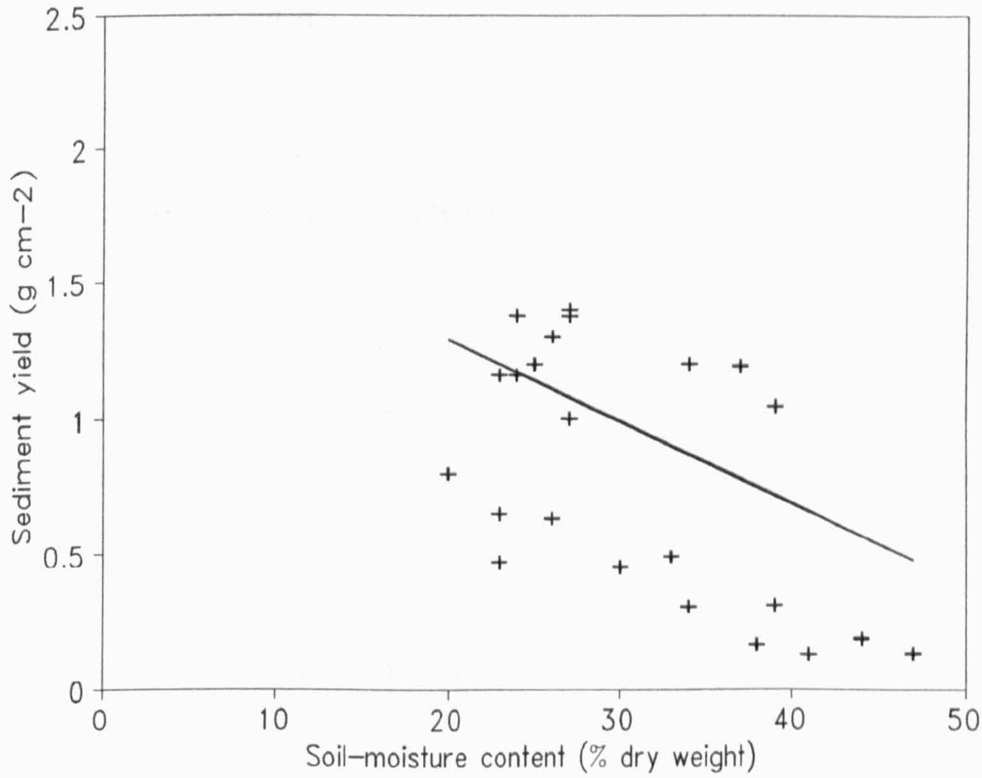

Figure 9.32 : Soil caps; soil-moisture content and sediment yield

$$E = 1.87 - 0.94Y_i \qquad (9.28)$$

(R^2 = 18.4%; St.error E-est. = 0.72 g cm^{-2}; n = 24; significant at 95% confidence level.)
Where Y_i is the density of ice (g cm^{-2}).

Although the relationship was statistically significant the standard error of the E-estimate was high; this may be because the relationship between sediment and ice yields is curvilinear as Figure 9.34 suggests; once the ice density is lower than a critical threshold it is expected that no sediment can be lifted.

9.4 MODELS OF NEEDLE-ICE TRANSPORT

When the needle-ice crystals melt the sediment that is held in the ice is usually deposited downslope from where it was lifted. In this section the movement of sediment in the laboratory experiments is compared with the distance of particle movement predicted by the previous models described in Section 3.3. A new statistical model is then developed.

9.4.1 Comparison between the distance of transport predicted by existing models and movement in the present study

Figures 9.35 to 9.40 show the distance of downslope sediment transport predicted by the gravity-fall model (Section 3.3.1a), the toppling model (Section 3.3.1b) and the Higashi and Corte model (Section 3.3.1a) on six different slope angles. The actual movement of stones monitored in the laboratory is also shown (the data are from both the disturbed and undisturbed samples).

To determine how closely each model predicted sediment transport, least squares analysis was performed on the difference between the predicted and actual distances of movement

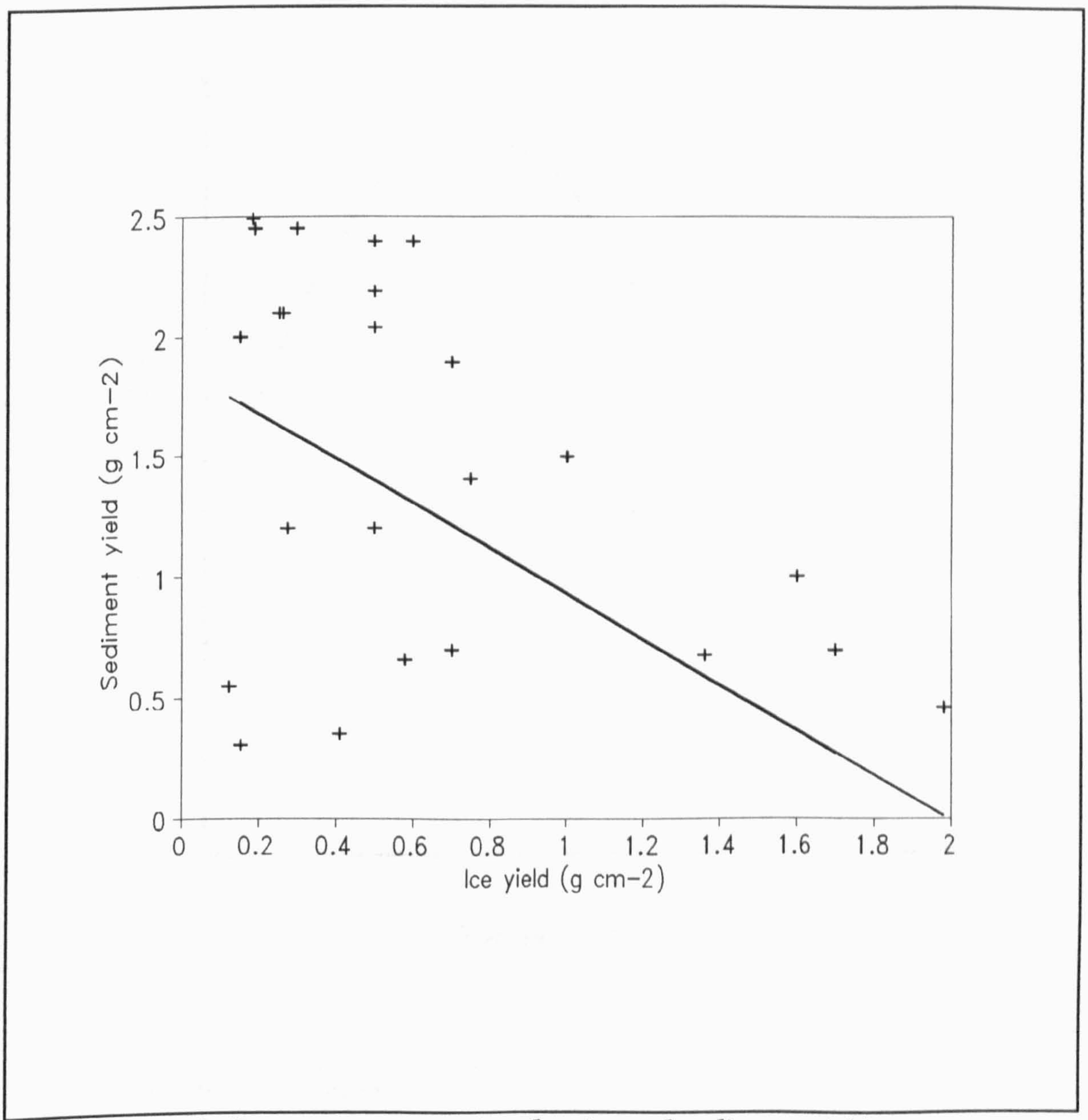

Figure 9.33 : Sediment aggregates; ice density and sediment yield

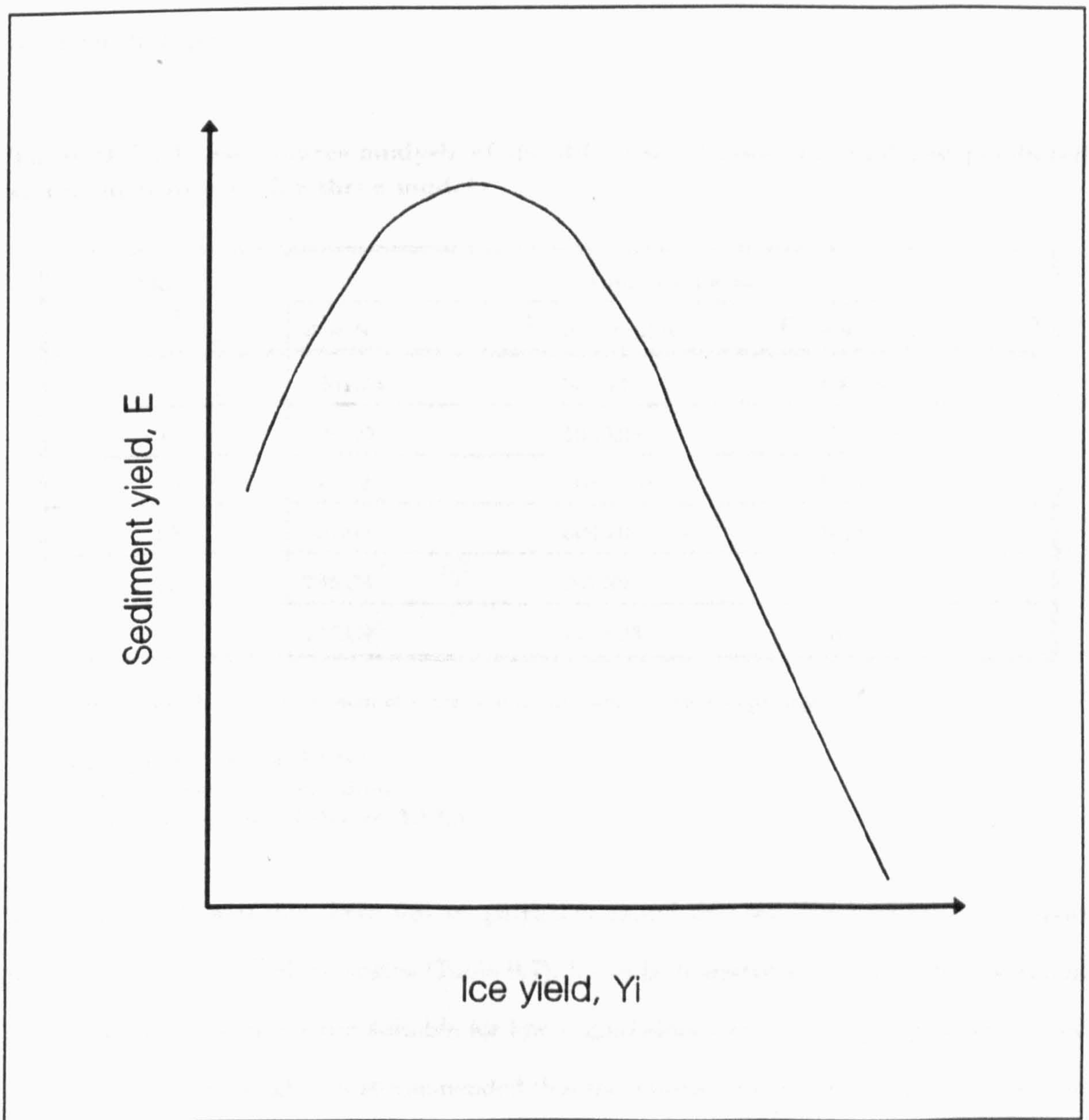

Figure 9.34 : Sediment aggregates; theoretical relationship between ice density and sediment yield

(Table 9.7). This used the following

$$SS=\Sigma(d_a-d_p)^2 \tag{9.29}$$

where SS is the sum of squares and d_a and d_p are the actual and predicted distances of sediment transport.

Table 9.7 : Least squares analysis of the difference between actual and predicted sediment transport for three models

Slope (°)	Sum of squares		
	d = h [1]	d = tanSh [2]	d = $(\tan S)^2 h$ [3]
5	1261.74	858.11	1004.44
6	1844.00	1309.25	1545.59
10	625.52	1036.291	1524.27
15	667.00	604.20	1011.23
22	736.25	947.22	1893.20
30	1174.89	1747.83	2870.69

(the model which reduces the sum of squares to a minimum for each slope angle is shaded)

[1] toppling model (Section 3.3.1b)
[2] gravity-fall model (Section 3.3.1a)
[3] Higashi and Corte model (Section 3.3.1a)

The analysis showed that there was no particular model that predicted sediment transport most accurately for all slope angles (Table 9.7). It can be tentatively suggested, however, that the gravity-fall model is more suitable for low angled slopes and the toppling model for the steepest slopes, although it is recommended that the analysis should be extended to include a wider range of slope angles.

In Chapter 8 it was shown that both crystal length and slope angle affected the distance that the markers were transported downslope. This is also illustrated by Figures 9.35 to 9.40; if movement was independent of slope angle then the data would cluster around the topple line, and if the slope was the primary determinant the values would mostly be between the gravity-fall and Higashi and Corte lines. In reality, most of the values fall between the topple and gravity-fall lines, and this indicates that both crystal length and slope angle are important.

9.4.2 A new semi-empirical model of sediment transport

9.4.2a Representing the influence of slope angle on downslope sediment transport.

The influence of slope angle on sediment transport was represented by a coefficient denoted by Θ. This was calculated empirically by performing regression analysis on the results of the relationship between crystal length and sediment transport for the 6, 15 and 30° slope angles, i.e. the h-coefficients (calculated in Section 8.3). The independent variable in the regression analysis was slope angle and the dependent variable was the h-coefficient from Table 8.3. This analysis gave the following equation to represent slope angle

$$\Theta = a + bS \qquad (9.30)$$

where Θ is the slope coefficient, S is slope angle (°), and a and b constants.

This calculation produced the regression line and equation shown in Figure 9.41. From this equation it was possible to calculate a coefficient Θ for any other slope angle. Figure 9.42 shows the regression line (the predicted values of Θ) and the values determined in the laboratory experiments (the 15° 'actual' values were calculated from data that was not used to produce the original equation). The good match between the actual and predicted values shows that this method is a suitable technique to represent the influence of slope angle on sediment transport. The values determined by this equation are higher than the tangent of the slope angle (5 times larger than tan(5) and 1.5 times larger than tan(30)). Thus, it appears that models that have used a component tanS have underestimated the influence of slope angle on the distance of sediment transport.

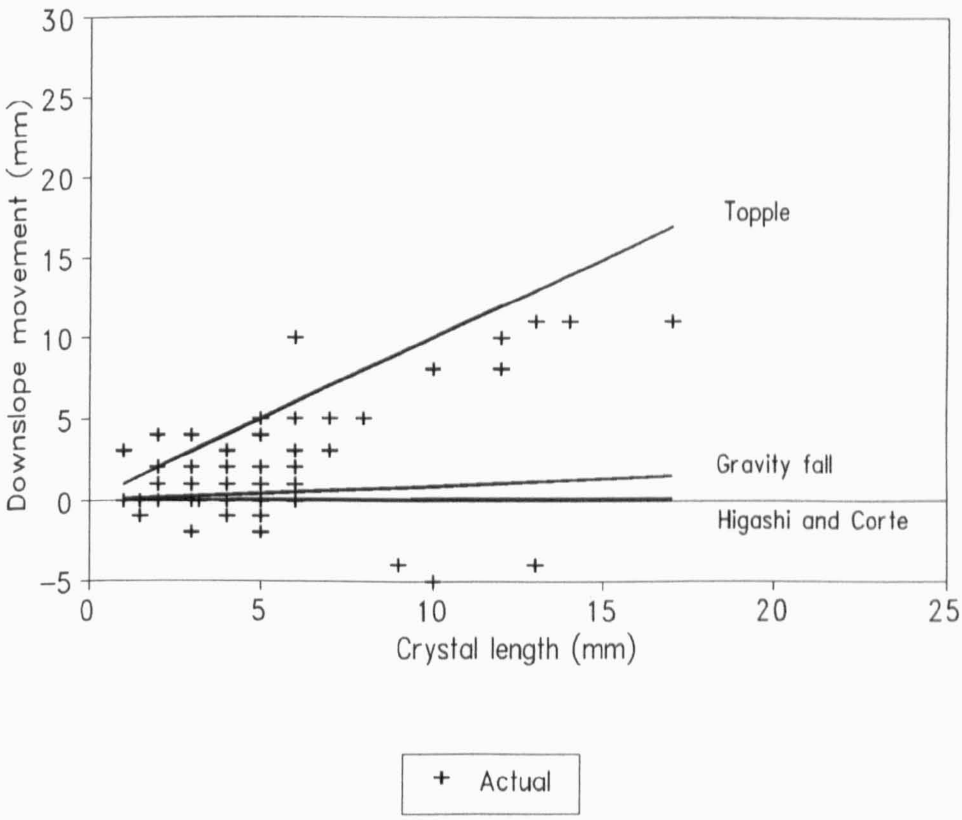

Figure 9.35 : Previous models of sediment transport; actual and predicted distances of transport; 5° slope

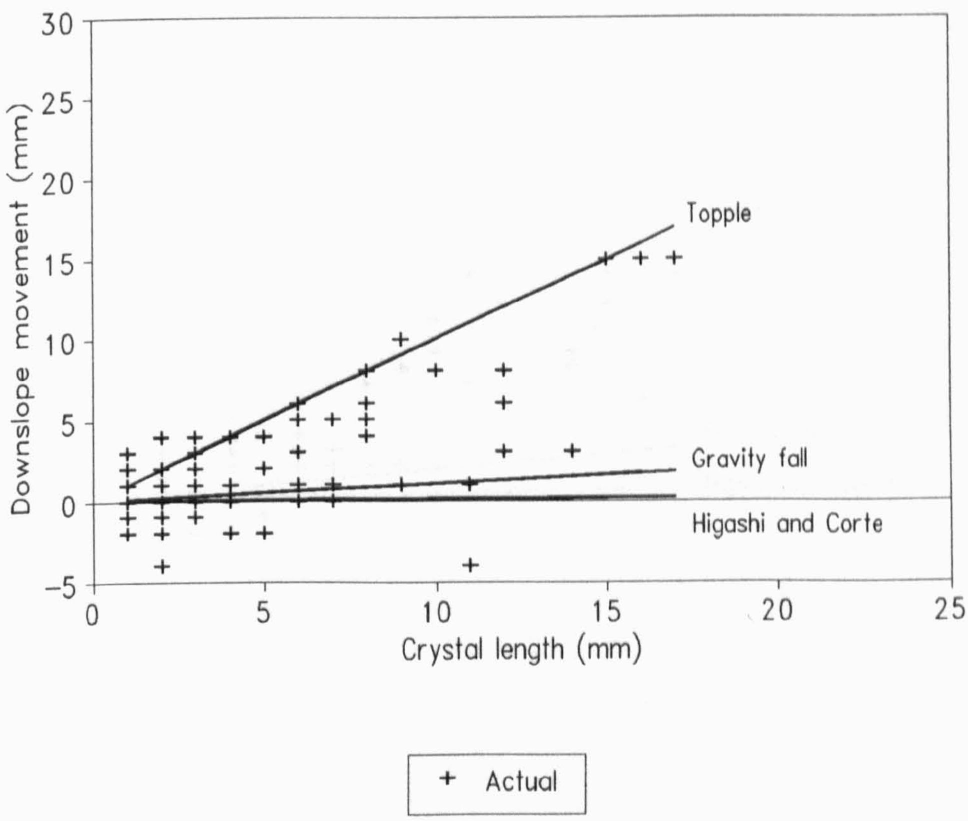

Figure 9.36 : Previous models of sediment transport; actual and predicted distances of transport; 6° slope

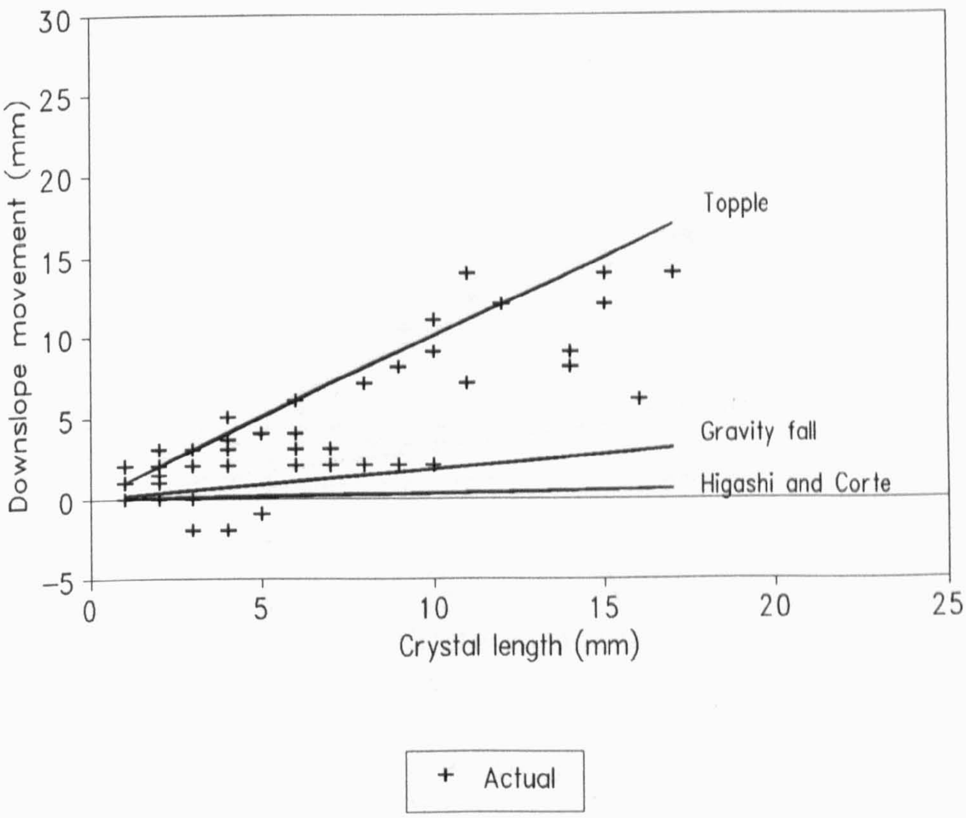

Figure 9.37 : Previous models of sediment transport; actual and predicted distances of sediment transport; 10° slope

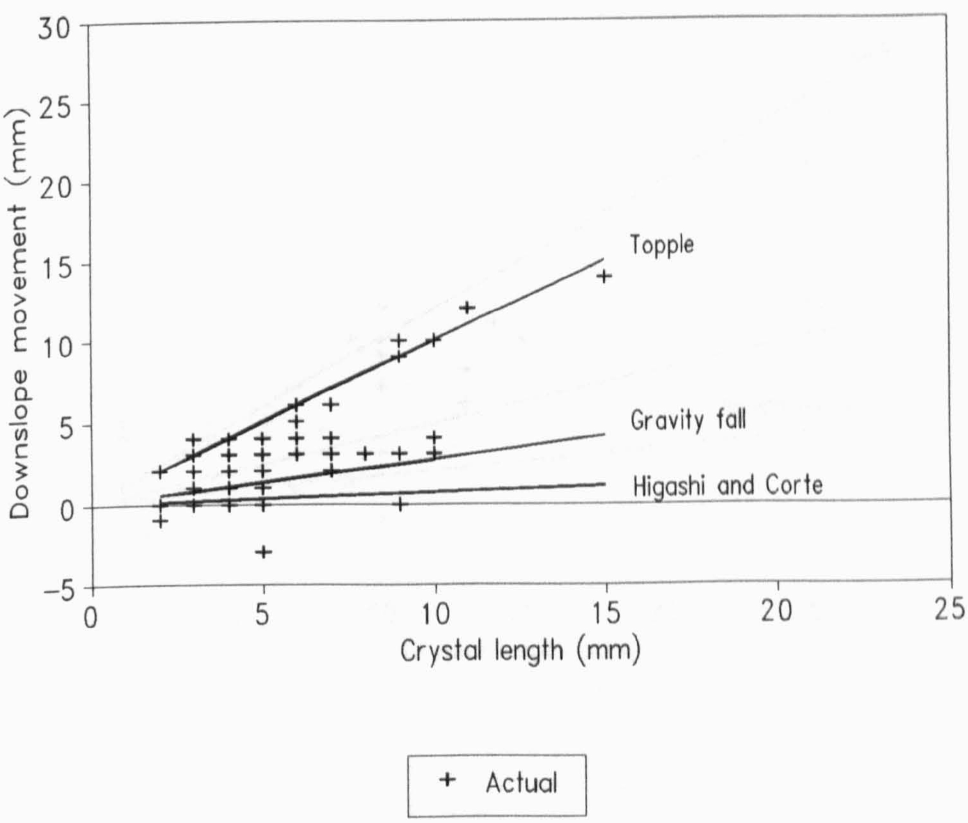

Figure 9.38 : Previous models of sediment transport; actual and predicted distances of sediment transport; 15° slope

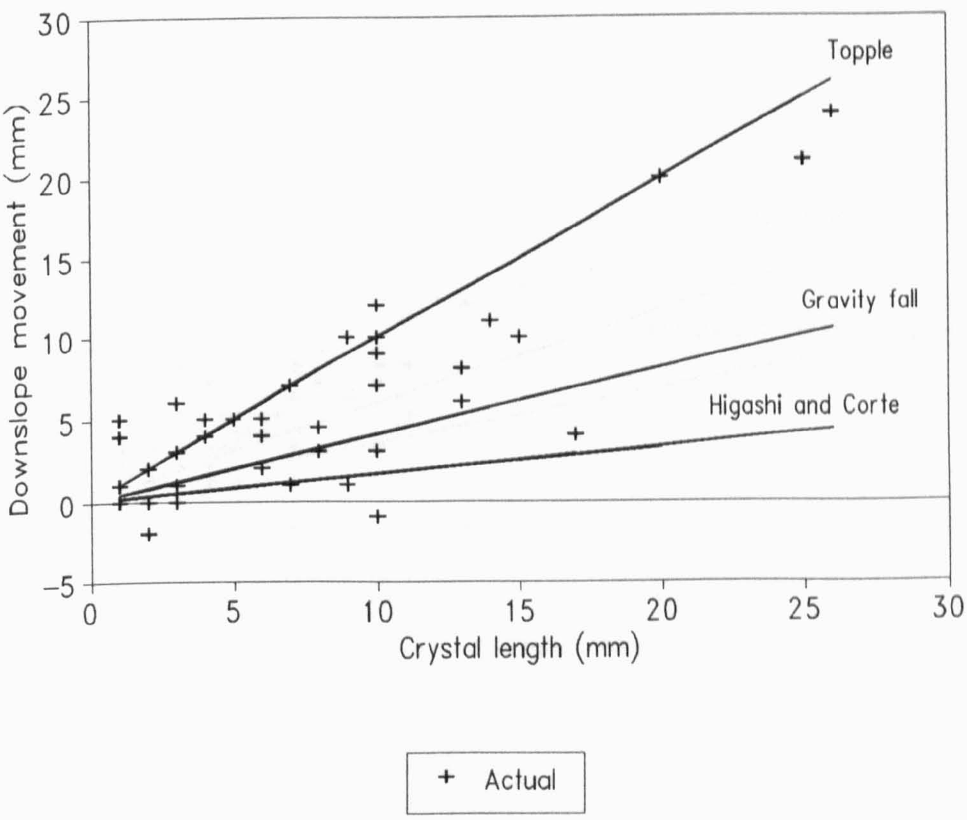

Figure 9.39 : Previous models of sediment transport; actual and predicted distances of transport; 22° slope

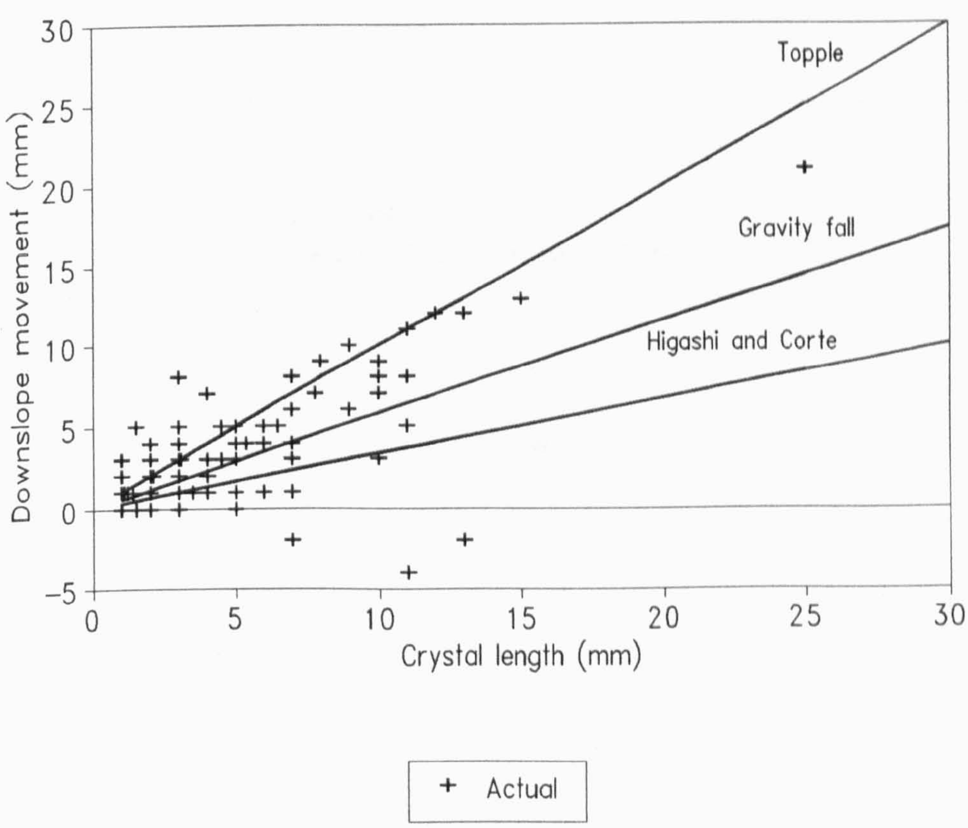

Figure 9.40 : Previous models of sediment transport; actual and predicted distances of transport; 30° slope

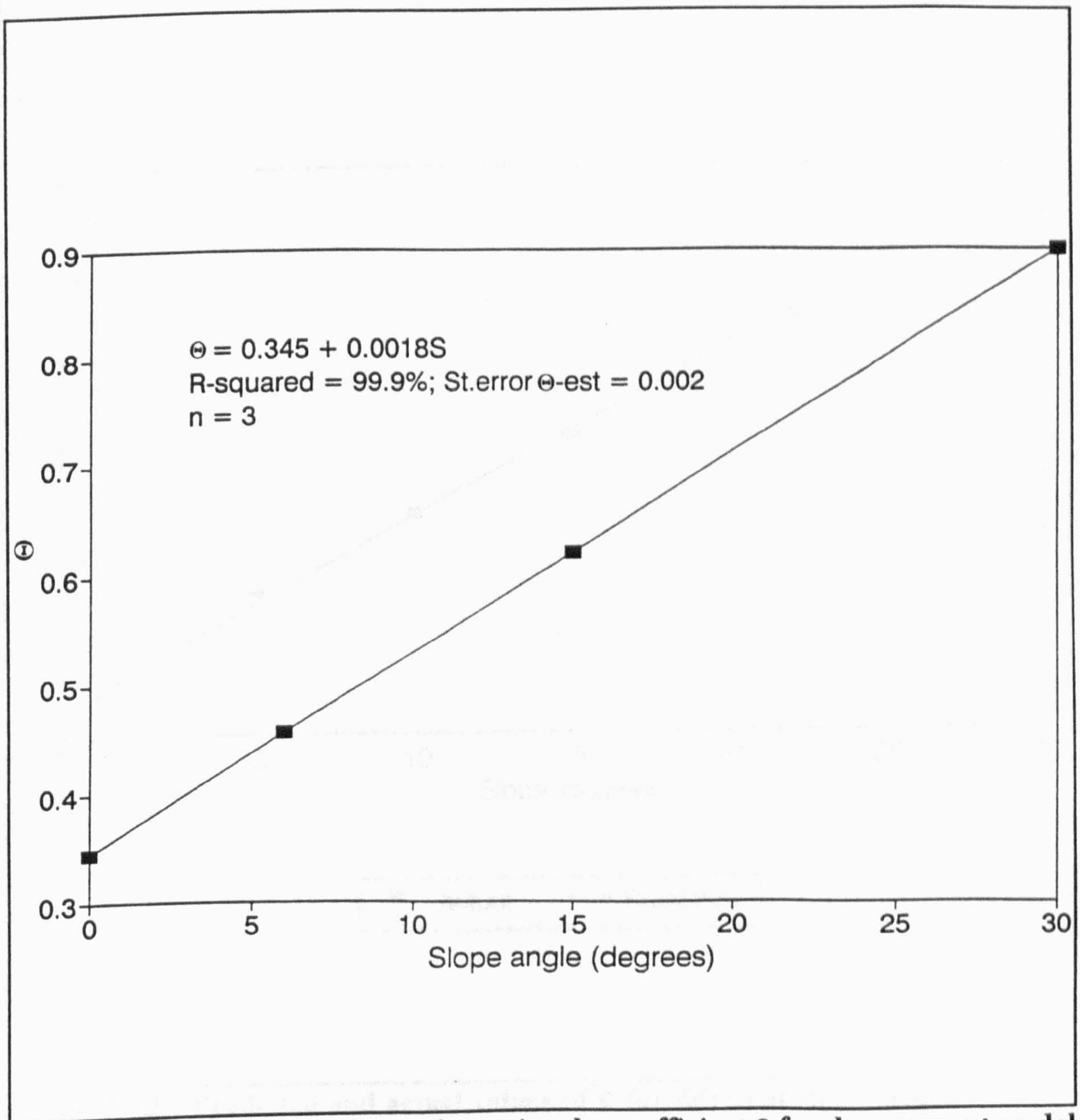

Figure 9.41 : Regression line to determine the coefficient Θ for the transport model

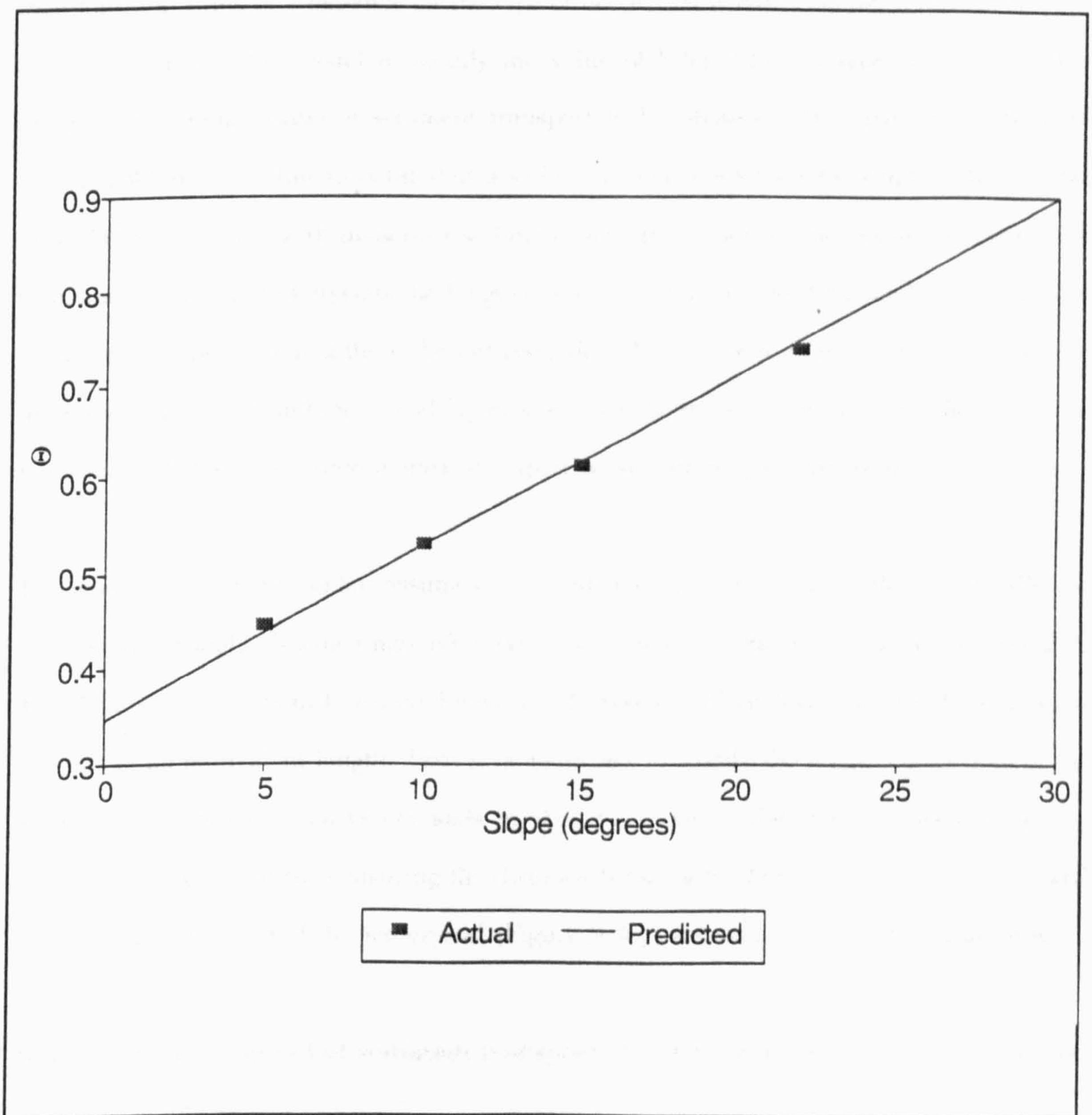

Figure 9.42 : Predicted and actual values of Θ for different slope angles

9.4.2b Representing the influence of needle height on downslope sediment transport. It was suggested in Section 8.3 that the location of sediment within the ice crystals determines the distance that the sediment is transported. In this new model, therefore, the value of h depends on the type of needle-ice crystal (Figure 9.43). A constant e was included in the model to modify the value of h for different types of crystal. This enables an average value of sediment transport to be obtained for a particular group of crystals. When the sediment is lifted as a soil cap h represents the total length of the crystal (e = 1). For crystals with dispersed sediment, half the length of the crystal is used (e = 0.5), and for multitiered crystals the length of the crystal minus the distance between the top of the crystal and the top of the sediment layer ($h = h - L_s$, where L_s is the distance between the top of the crystal and top of soil layer, and e is then represented by 1). (If there is more than one sediment layer then a separate equation should be used for each layer.)

The model as presented so far, assumes, as do other models of transport, that the needle-ice crystals are straight. Needles may often be curved, however (Sections 3.3.1a and 10.4.2b). The distance of sediment transport from curved crystals will be less than that from straight crystals of an equivalent length. Thus it is necessary to modify the length component of the model to account for the curved crystals (so that it is reduced when the crystals are curved). This may be achieved by measuring the distance between the base of the needle-ice crystal sediment and the end of the ice crystal (Figure 9.44), and using this as the value of h.

9.4.2c The new model of sediment transport. The final form of the sediment transport model is as follows

$$d = \theta e h \tag{9.31}$$

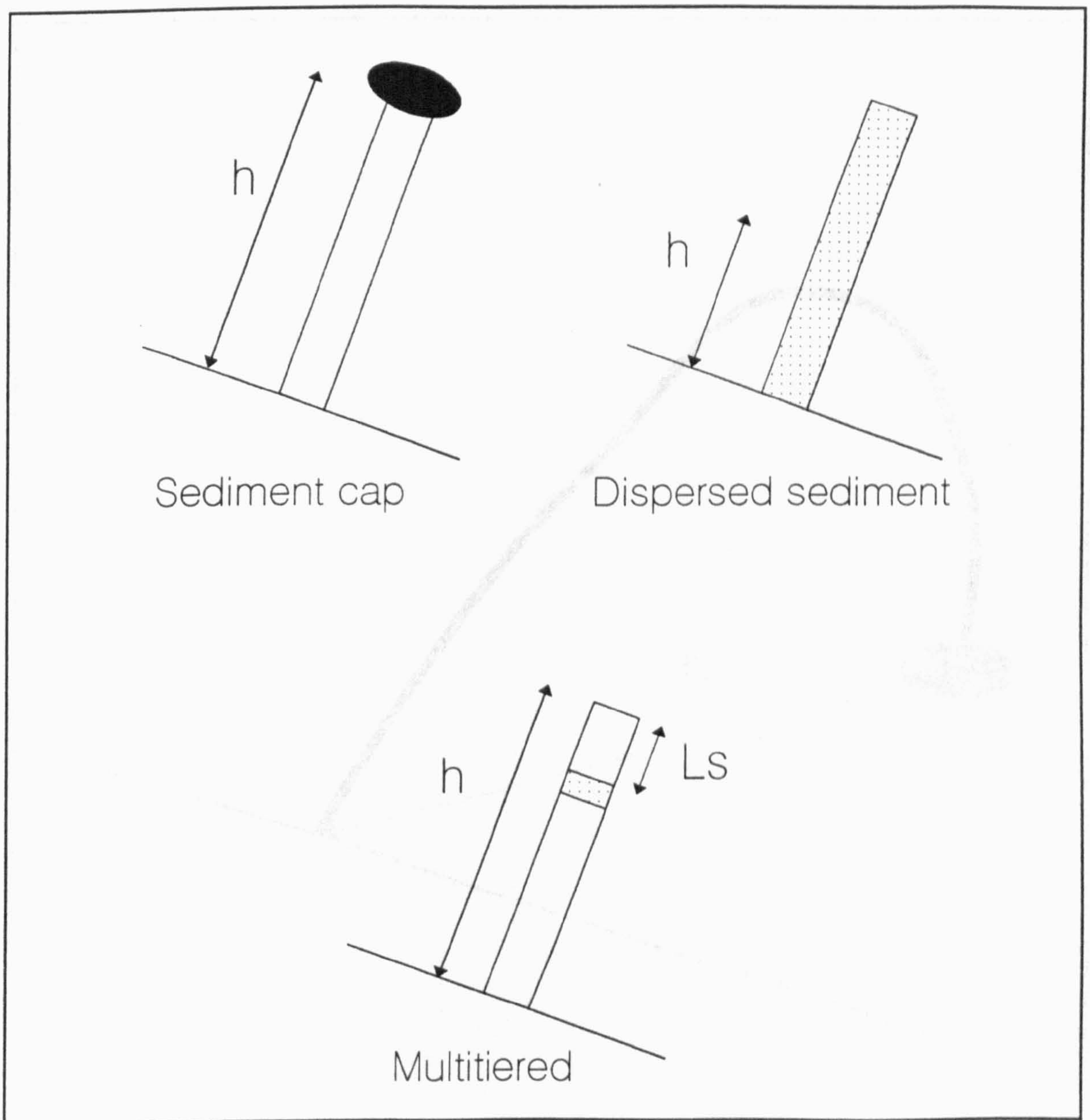

Figure 9.43 : A technique to represent needle height for different types of needle-ice crystal in the sediment transport equation

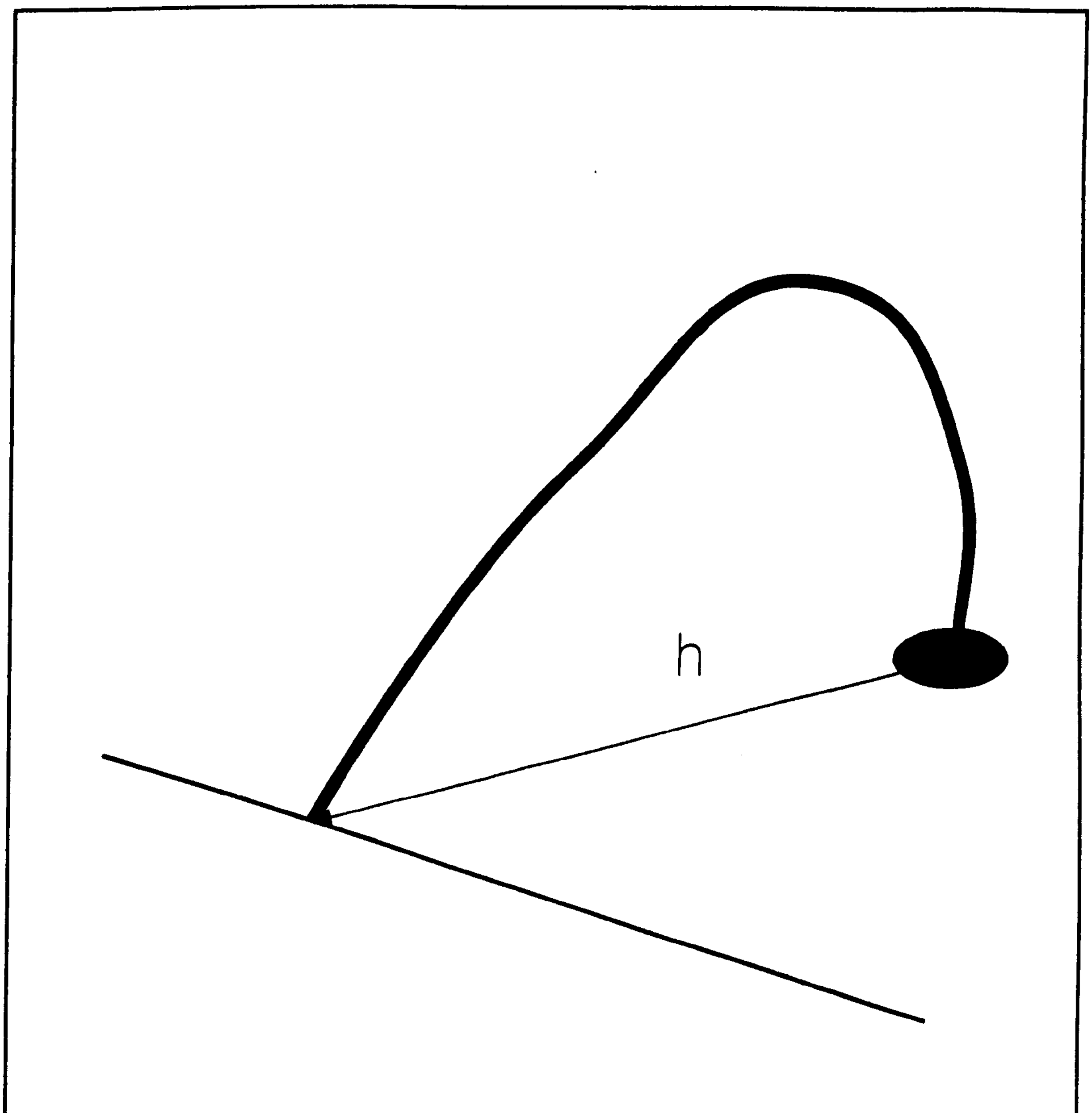

Figure 9.44 : A technique to represent needle height for curved crystals in the sediment transport equation

The model was used to see how accurately it predicted the movement of markers in the laboratory study. It could only be tested for situations where the sediment was lifted on top of the ice crystals (i.e. $e = 1$), given the unreliability of the data where sediment was incorporated into the needle-ice crystals (Section 5.5.2).

The actual and predicted movements from the six slope angles are shown in Figures 9.45 to 9.50 (Θ was the value predicted from Equation 9.30). Least squares analysis, as described above, was performed on the difference between the actual and predicted sediment movement (Table 9.8). The analysis showed that the new model reduced the difference between the actual and predicted movement by at least 50% for all slope angles, with the exception of the 30° experiment. The small reduction in the sum of squares for the 30° experiments probably indicates that on this slope the needles were more likely to topple, and thus slope angle did not have as great effect on the distance of transport as on lower slope angles. Figure 9.50 shows that on the 30° slope the distance of transport was usually underestimated.

Table 9.8 : Least squares analysis of the difference between actual and predicted distances of sediment transport as predicted with the new model

Slope (°)	Sum of squares	Smallest sum of squares from previous models
5	561.00	858.11[b]
6	918.58	1309.25[b]
10	329.14	625.52[a]
15	329.08	604.20[b]
22	437.25	736.25[a]
30	1158.00	1174.89[a]

[a] toppling model
[b] gravity-fall model

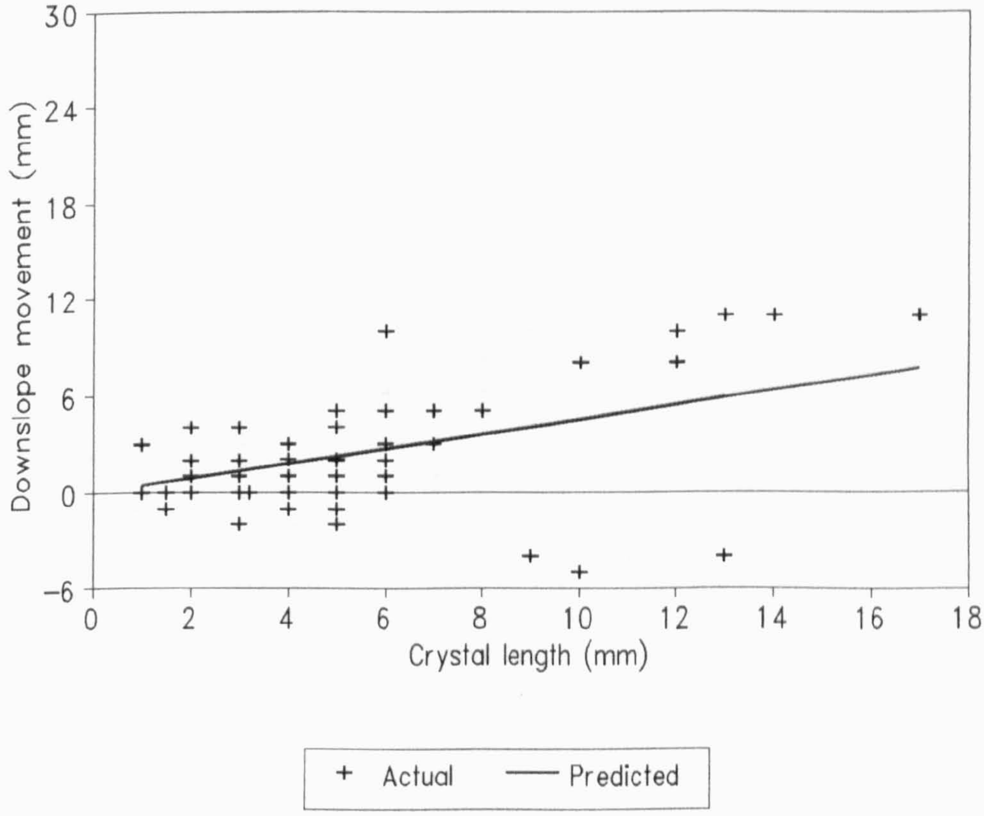

Figure 9.45 : Downslope sediment transport predicted using the new model and actual downslope movement; 5°slope

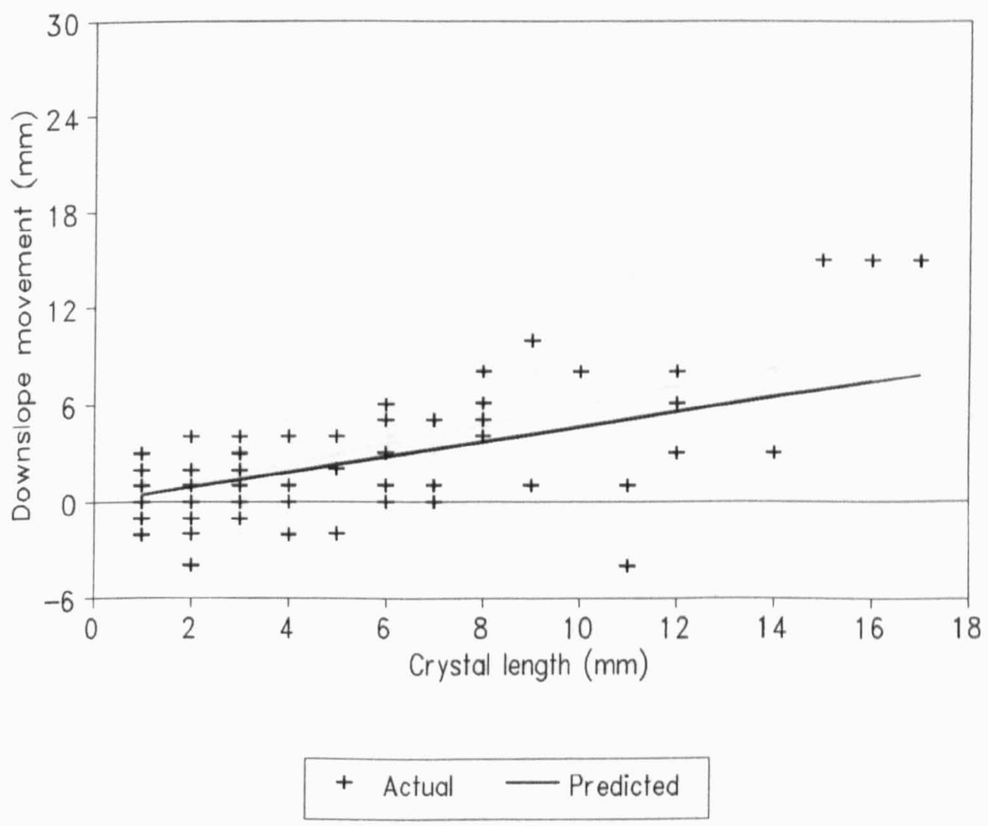

Figure 9.46 : Downslope sediment transport predicted using the new model and actual downslope movement; 6°slope

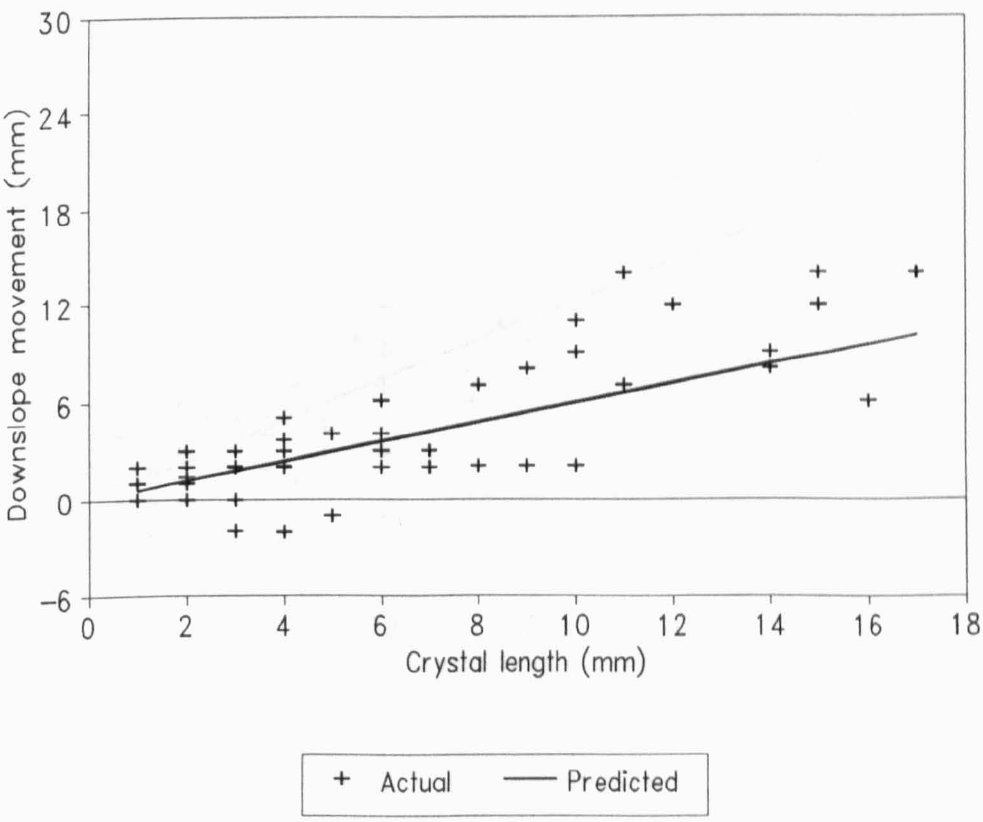

Figure 9.47 : Downslope sediment transport predicted using the new model and actual downslope movement; 10°slope

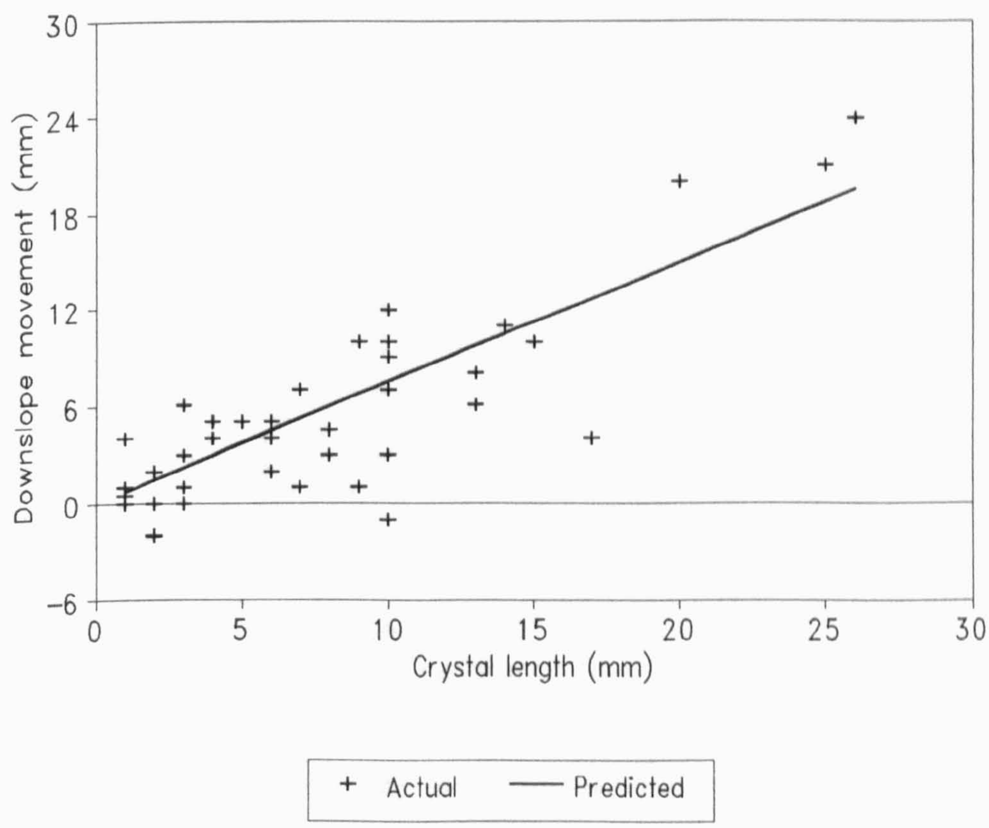

Figure 9.48 : Downslope sediment transport predicted using the new model and actual downslope movement; 15°slope

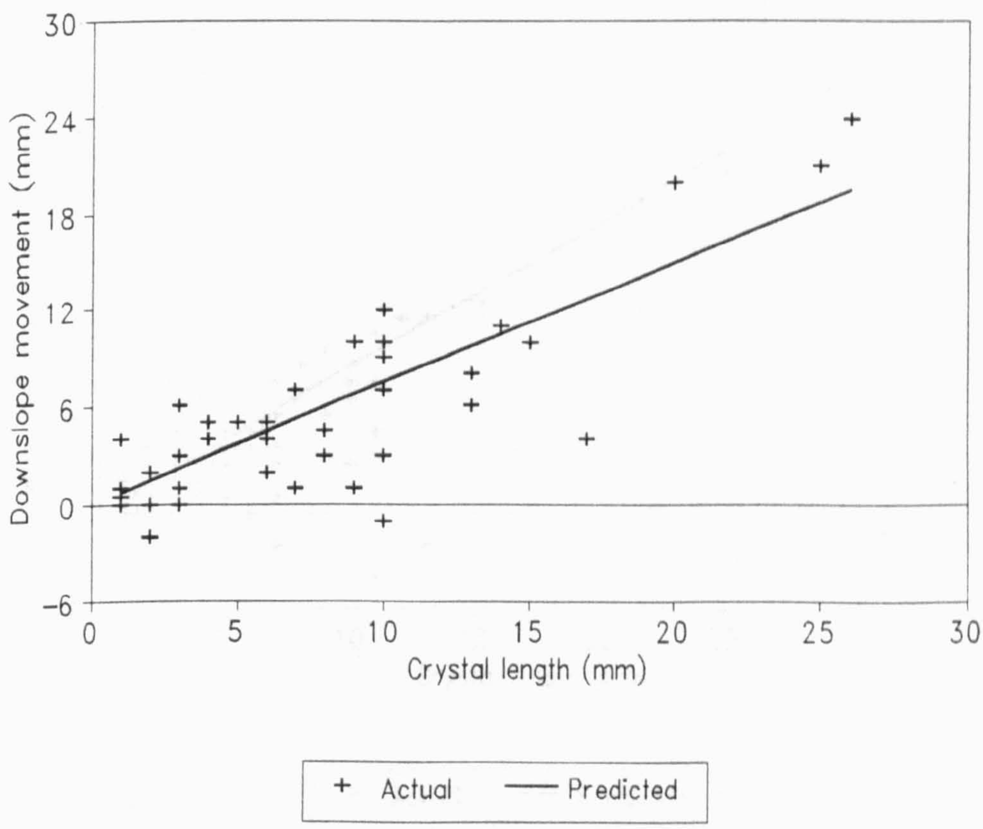

Figure 9.49 : Downslope sediment transport predicted using the new model and actual downslope movement; 22°slope

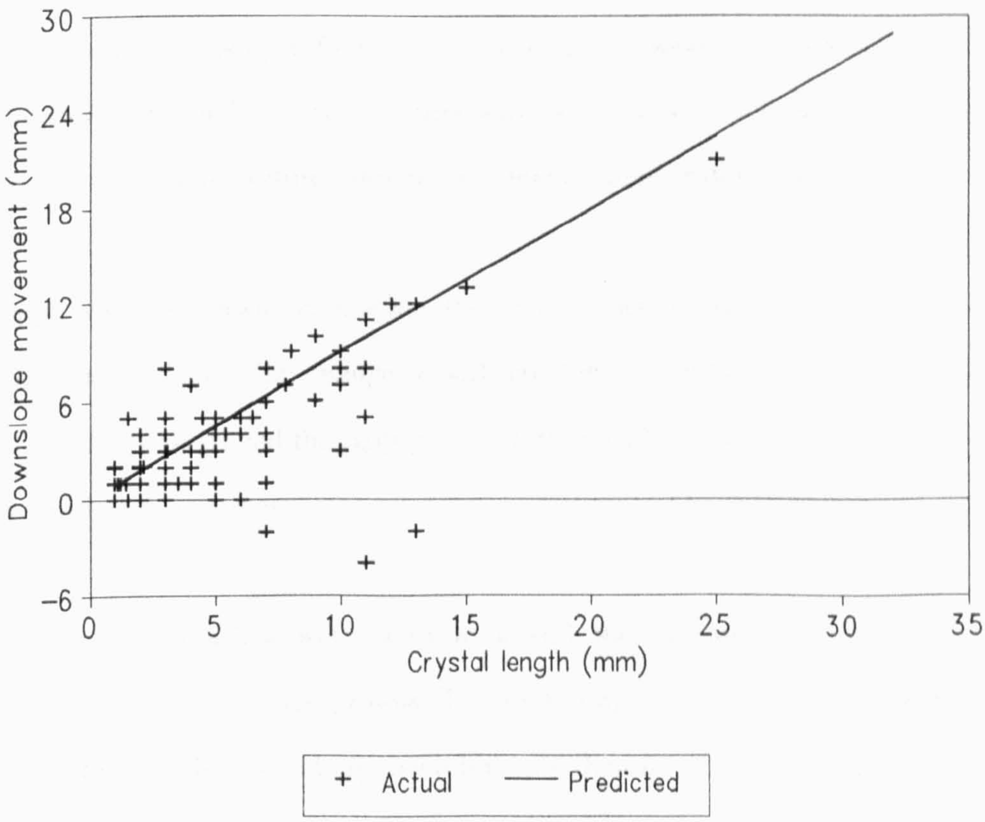

Figure 9.50 : Downslope sediment transport predicted using the new model and actual downslope movement; 30°slope

9.5 CONCLUSIONS

This chapter has presented a series of new, albeit simple, regression-based, models that attempt to predict the growth and sediment incorporation and transport effects of needle-ice growth. Problems with existing models that attempt to represent needle ice have been identified and this has aided the development of the new models.

The length of needle-ice crystal that will grow in a given freezing cycle was predicted reasonably accurately using information of soil-surface moisture content and a new index termed 'segregation time'. Segregation time was the duration of sub-zero temperatures above a certain threshold temperature after the nucleation temperature was reached.

An attempt was also made to predict the rate of needle growth during two individual experiments using data of the change in soil-moisture content and soil-surface temperature. Whilst this closely predicted the <u>pattern</u> of growth, it did not predict the <u>value</u> of the growth rate with sufficient accuracy.

Three different approaches were used to model the amount of sediment that will be incorporated during needle-ice growth. The first simply related the sediment yield to the length of needle ice. The second approach linked sediment yield to moisture and temperature variables that represented the cessation of needle-ice growth. Sediment yield was inversely related to soil-moisture content and segregation time. This form of model predicted sediment yield more accurately than models that just use crystal length. In the third approach the needles were split into different needle types and models developed for each. For crystals with dispersed sediment and monocyclic multitiered needle ice, crystal length predicted sediment yield with reasonable accuracy. For soil caps, on the other hand, the soil-surface moisture content was more important, and for sediment aggregates, the ice yield provided the greatest explanation of sediment yield.

An algorithm was developed to predict the type of needle-ice which will grow in a given freezing event, on the basis of soil-moisture content and soil-surface temperature. This algorithm was tested on the laboratory data and predicted the needle type for 55.3% of the experiments. The main problem with the algorithm was that it could not be used to predict the lift of sediment aggregates.

The transport of sediment by needle ice was also predicted using a new semi-empirical model, based in part on the previous models discussed in Chapter 3. The model included a slope component - the slope coefficient, and a needle height component. The slope coefficient had a greater influence on the distance of sediment transport than allowed for in models which use the value of tanS. The height component can be modified to take into account sediment incorporated at different levels within the crystal and curved crystals. This new form of model predicted sediment transport more accurately than the previous models.

It is expected, however, that the models developed in this chapter may be improved with the addition of further information. Possible improvements are discussed in the following chapter.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

10.1 INTRODUCTION

The purpose of this chapter is to first make recommendations regarding how research into the erosion and transport of sediment by needle ice could be extended in the future. Following this, in the light of these suggestions, the wider implications of this work are discussed, and the conclusions of the needle-ice experiments are presented and summarised.

10.2 FUTURE WORK

In light of the results from this study, several areas for future work have been identified. These have been split into four themes which cover laboratory techniques, needle-ice growth, sediment incorporation and sediment transport.

10.2.1 Improvements to the laboratory techniques

10.2.1a Measurement of heat flow in the soil. A large component of this study has assumed that the cessation of needle-ice growth occurred when there was a disturbance in the balance of heat flowing to and from the freezing front. These fluctuations in heat flow have been inferred indirectly, given fluctuations in the temperature and moisture content at the soil surface and within the soil profile. Future studies should attempt to measure heat flow within the soil and at the soil surface directly. This may be difficult because the monitoring techniques (e.g. heat flux plates) often affect the flow of heat itself.

10.2.1b Measurement of fluctuations of soil-moisture content. In several areas of this study (e.g. Sections 6.3 and 7.3) it has been shown that the growth of needle ice and the incorporation of sediment into the ice crystals was affected by pulses of moisture flow. It was not determined why these fluctuations occurred, however, and future studies should therefore aim to investigate this further. It may be necessary to use instruments that are more sensitive to variations in moisture content than the elements used in this study.

10.2.1c Use of time-lapse photography or video. The studies by Hayward and Barton (1969) and Brockie (1968) used time-lapse photography to monitor the growth of needle ice and the transport of particles by the ice crystals. It is recommended that future field and laboratory studies of needle ice should use a video camera to record the growth and melt of needle ice and the mechanisms of sediment transport which may occur. Using this technique it may be possible to identify the processes which occur during the growth of needle ice with dispersed sediment. Additionally, it will show which type of needle ice grew in individual freezing cycles without being present at the field site during freezing. This information can then be used in models to predict sediment yield (Section 9.3).

10.2.2 Needle-ice growth

10.2.2a Field verification of laboratory results. This study has used data from a series of laboratory experiments with only limited reference to field data. It is recommended, therefore, that a future field study should make use of similar instrumentation to that used in the laboratory; this will enable the hypotheses and models developed in this present study to be tested under natural conditions of cooling and soil moisture. It will be particularly interesting to determine whether high frequency fluctuations in soil-moisture content occur in nature.

10.2.2b The formation of curved needle ice. Curved needle-ice crystals sometimes grew during the freezing cycles, often at the edge of the sample box (Plate 7.4). They are important because they affect the distance that included sediment is transported when the ice melts. In a field situation the growth of curved needles is usually attributed to the existence of a strong wind prevailing from one direction, with the needles bending towards the wind. In the laboratory this process could be reproduced by placing a fan at one side of the sample box; the needles bent towards the fan.

In most of the needle-ice simulations, however, the soil block was sealed in a cooling chamber where there were no strong currents of air, and thus it is expected that the needles became curved as a result of another process. Several theories have been put forward to explain crystal curving; these advocate the effect of reduced moisture content or chemical contamination of the soil on the process of needle-ice growth, for example. No firm conclusions have been made regarding the growth of curved crystals in this experiment, but, given that the curved crystals grew at the edges of the box where the contributing area of moisture is reduced, it appears that the moisture-limited theory is the most appropriate. More research should be undertaken into this subject.

10.2.2c The chemical/physical nature of ice segregation. It has been questioned whether moisture migration during needle-ice growth is a chemical or physical process. Some advocate that moisture migration cannot occur without clay particles in the soil, and thus is a chemical process. Some authors (e.g. Low and Lovell, 1959; Williams and Smith, 1989) have stressed the importance of the role of the adsorbed layer of moisture for soil heaving. Others, however, state that moisture migration is a physical process and will occur in chemically inert substances (e.g. Dash 1989a, 1989b).

To investigate the nature of ice segregation several preliminary experiments were conducted using natural and artificial 'soils'. These included building 'sand', 'sand' with the clay particles washed out and three types of glass spheres with diameter 2 mm, 50 μm and 2 μm. Needle ice was grown on both types of 'sand' and the 50 μm glass 'soil' but not on the other media. This suggests that needle ice can grow without clay particles, and therefore that ice segregation is a physical process. It appears, therefore, that moisture migration occurs as a result of the capillary flow of moisture to the freezing front. The absence of needle-ice growth in the coarsest glass soil suggests that small particles are required for capillary flow to occur, whilst the finest glass soil was probably too fine and prevented moisture flow. This subject is clearly an area which requires further research.

10.2.2d Improvements to the model of needle-ice growth. The model of needle-ice growth as presented in Equation 9.6 predicted the length of crystal quite accurately. However, there are ways in which this could be improved with the inclusion of additional data. For example, the model assumes that the rate of needle-ice growth is the same throughout the freezing cycle. It was shown in Chapter 6, however, that the rate of growth often decreased during the freezing cycle. This reduction in growth may possibly be represented as a power law of the segregation time.

Also, Equation 9.6 uses only one value of nucleation temperature. The nucleation temperature, however, varies depending on the rate of soil-surface cooling which in turn is dependent on the soil-moisture content and the initial soil-surface temperature. Using data equivalent to that in Figure 6.6 it should be possible to determine the nucleation temperature for a particular experiment. The time at which ice segregation ceases will also depend on soil-moisture content, and this should also be taken into account in a new model, such that

$$D_s - D_N - D_C \qquad (10.1)$$

Where D_s is 'segregation time', D_N the duration of sub-zero temperatures after the nucleation temperature is reached and D_C the number of hours that temperature is below the minimum threshold for needle-ice growth. (It should be noted, however, that because the temperature during a freezing cycle often fluctuated D_C represents the number of hours that T_s was below the minimum temperature, rather than the number of hours of sub-zero temperature following the time that the minimum temperature was reached.)

Needle-ice growth also ceases when the soil-moisture content falls below a certain threshold (Chapters 6 and 7). An additional term in the model of needle-ice length could therefore include a component which represents the number of hours that moisture content is below that threshold.

10.2.3 Sediment incorporation by needle ice

10.2.3a The role of ion concentrations in sediment incorporation and needle-ice growth. The cessation of needle-ice growth in this study has been attributed to imbalances in the flow of heat to and from the freezing front. It is possible, however, that growth may cease as a result of fluctuations in the chemical characteristics of the soil moisture, although time restrictions did not allow this to be investigated here.

Many fieldworkers (e.g. Outcalt, Gray and Benninghoff, 1989; Outcalt and Hinkel, 1989; Outcalt, Nelson and Hinkel, 1990) have monitored the electrical potential of freezing soils to give information about the relative soil-water ion concentration in the soil using 'C' probes. 'C' probes are designed to monitor the electrical potential of the soil moisture. These data are used to calculate relative soil water ion concentration, known as the 'C' index. It is argued that the use of these probes augments the soil-temperature data (Outcalt and Hinkel, 1989). From this electrical potential information the non-conductive heat flow processes in the soil can be established. (These can include phase changes, vapour diffusion and water advection.)

It may be possible that if there is a high ion concentration in the soil water then freezing may be prevented (e.g. Henry, 1988). Therefore, if the flow of water with a high ion concentration occurs in frequent pulses to the freezing front then ice segregation may cease. The role of chemical contamination in soil freezing has already been recognised in some studies, for example, additives have been used to decrease the temperature at which ice nucleates (e.g. Brandt, 1972). It is recommended that future studies of needle ice should conduct a similar type of investigation to those mentioned above and use 'C' probes or comparable instrumentation to monitor the ion concentration of soil moisture, and to investigate the effect of different ion concentrations on needle-ice growth.

10.2.3b Preferential incorporation of coarse material. Data from both laboratory and field samples have shown that there was a significant difference between the bulk and incorporated sediments. Only sediment less than 2 mm was analysed here, however, and additional experiments should be undertaken which include coarser sediments.

It was suggested in Section 7.4 that if sediment is lifted as a frozen soil cap then there will probably be no difference in grain-size composition between the lifted soil and the bulk soil from which it was raised. In the present study, however, this theory could not be tested because as a result of the small amounts of sediment that were lifted, the incorporated soil was taken from all types of needle ice together. It is suggested that the grain-size composition of soil lifted and incorporated by different types of needle ice should be analysed individually to assess whether the process of lift and incorporation influences the characteristics of the lifted soil in comparison to the bulk soil.

10.2.4 Needle-ice transport

10.2.4a Transport of incorporated particles. In Chapter 8 it was suggested that sediment incorporated into the needle-ice crystals was transported shorter distances than that lifted as a soil cap. The method used to monitor transport from within the ice was not satisfactory, however. It is therefore necessary that new techniques are developed whereby it is possible to determine from where on the soil surface marker particles are lifted within the ice, and then how far they are transported downslope.

10.2.4b Future developments of the transport model. The model of sediment transport developed in Section 9.4 predicted the amount of sediment transport on the laboratory samples more precisely than the previous models. There are ways in which this model could be developed further, however, with the inclusion of additional data.

The model was developed using data from experiments which monitored the movement of stones downslope. Short-term pilot investigations undertaken as part of this study determined that under the same environmental conditions sand particles move smaller distances than stones. Thus, the value of coefficient e (Equation 9.31) should be modified to represent different types of sediment (in terms of size and shape). A smaller value of e will be required to represent smaller particles. The values of the coefficient should be determined with a series of laboratory experiments.

In a field situation the amount of meltwater and the speed at which it is released onto the soil surface are important for promoting the transport of particles in streams of melt (Section 3.3.1c). In the laboratory experiments, however, there was usually insufficient water released onto the soil surface to cause markers to be transported by meltwater. This is a result of the relatively small amount of needle ice that was available to be melted. Nevertheless, it is expected that the longer the ice crystals, and the higher the early daytime temperature, the more moisture that will be released in a short time. Thus, there is a greater potential for meltwater flow. This is difficult to represent, however, given the large number of variables that affect the process, such as soil moisture, depth of water flow (which will affect the size of particle that could be entrained), speed of release of melt and amount of evaporation. Future studies should attempt to monitor these variables and determine their influence on the amount of meltwater transport.

10.3 WIDER PERSPECTIVES OF THE PRESENT STUDY

This section discusses the wider implications of the needle-ice project and the position of the project in relation to current paradigms in science.

Clark (1991) argued that there are currently three major perspectives in the nature of scientific thought:

i) interaction between the reductionalist and holistic viewpoint;

ii) trend from disciplinary to interdisciplinary focus;

iii) the acceptance of uncertainty within natural systems, particularly the movement from linear to non-linear systems.

The needle-ice project has encompassed all of these approaches, and this is discussed briefly below.

Whilst the study has focused on one particular aspect of frozen ground it has attempted to make conclusions that are relevant to other forms of ice segregation. In this respect a theme in some aspects of this study has been the similarity of processes which occur during the growth of needle ice and other forms of soil ice. Until now, however, there has been only a limited-cross fertilisation between the substantial needle-ice literature and the literature relating to other forms of segregated ice. This may, in part, have occurred because the research into these two areas is undertaken by distinct groups of scientists; needle-ice research usually falls into the domain of geomorphologists and geologists, whilst ice lenses etc are usually investigated by ice physicists. It is therefore evident that a multidisciplinary approach is required for the study of needle ice, and this project has attempted to bring the two areas of research together, to show how theories developed in one area can be used in the other.

With regard to a non-linear approach, this study has stressed the complex response between needle-ice growth and changes in soil-moisture content and soil-surface temperature, for example the curvilinear relationship between needle-ice length and soil-moisture content, or between sediment yield and crystal length. Irregularities in the freezing soil system have also been discussed, for example, the pulses observed in moisture flow, and the their effect on the rate of crystal growth. Now that these complex responses have been recognised, it is important that the factors which cause them are identified (Section 10.2).

10.3.1 Possible wider implications of the needle-ice project

The models developed in this study may be used in a predictive capacity to determine the impact of needle ice in terms of soil erosion, vegetation destruction, etc. Equation 9.6, for example, may be used in conjunction with standard meteorological data to predict when needle-ice growth will be the most prolific, During these periods it would be advisable to employ frost protection measures, e.g. mulching, to prevent damage to soil and vegetation.

Knowledge of the processes by which needle-ice growth and sediment is incorporated may become valuable as the economic and planning pressures in periglacial regions increase (e.g. Hursh, 1948; Crory *et al.*, 1984; Polar Research Board, 1984; Lawson, 1986), and it is anticipated that the sediment yield models may be an addition to soil erosion models that have not included the effect of frost. Where river banks are affected by needle ice it may be possible to determine how much sediment will be released into the river as a result of sediment incorporation into the ice. It will therefore be possible to determine the contribution of needle-ice erosion to the total sediment yield carried by the river.

Throughout this study the importance of moisture in terms of needle-ice growth has been stressed. Thus, if needle-ice damage is to be minimised it seems important that to ensure that the soil underneath structures, and in fields, is either well drained or highly compacted, in an attempt to reduce moisture migration. The same argument can be followed to ensure that other forms of ice segregation such as ice lenses, do not form.

10.4 CONCLUSIONS

In the light of the above discussion, this section presents the main conclusions from the needle ice study.

From the literature review (Chapters 2, 3 and 4) it was apparent that whilst there has been a large body of work concerned with needle ice, many publications have tended to base their discussion on only one aspect of the subject (e.g. growth processes in the field, sediment disturbance or laboratory investigations) and there have been very few integrated studies. The present project sought to analyse needle-ice growth, sediment disaggregation and sediment transport by ice crystals. As the study was laboratory-based the environment for needle-ice growth could be controlled closely and monitored in detail, and as such the study provides a useful addition to the field studies by other authors.

10.4.1 The needle-ice experiments

The experimental design used in this study was developed from that used in preliminary studies by Parker (1987), Pickering (1988) and Polkinghorne (1988). The use of a microcomputer made it possible to control soil-surface temperature so that the surface cooling rate followed specified patterns. This allowed the influence of cooling rate on needle-ice growth to be identified. The incorporation of a datalogger for the first time into a needle-ice study allowed the continuous monitoring of the length of needle-ice crystals and temperature and moisture contents in the soil profile. The use of soil-moisture elements (also for the first time) was seen as a particularly important development because it was possible to monitor the movement of water towards the freezing front, and then to determine the influence of soil-moisture content upon needle-ice growth. It is anticipated that now these techniques have been tested in a laboratory study they can be easily used in studies of not only needle ice but also other periglacial and small-scale geomorphic features.

The findings presented in this thesis are based on over 200 experiments which lasted between 8 h and 36 h. Two types of soil samples were used which were taken from locations where needle ice was observed to grow naturally. Samples DSE and DSB were remoulded samples; they were sieved and compacted before use in the experiments. Sample DSE_1 was used in a preliminary series of experiments that were designed to test the apparatus. The USB samples were undisturbed, and were transferred from a Birmingham river bank into the apparatus as a block, without modification.

To determine whether soil disturbance had any influence on needle-ice growth, experiments were conducted on disturbed (DSB_1) and undisturbed (USB_1) samples of soil taken from the same field location. Soil disturbance influenced the density of cover of needle-ice crystals on the soil surface, the range of needle-ice lengths and the sediment yield from the ice crystals. On the disturbed sample the cover of needle-ice crystals was almost continuous and the range of lengths was small. During individual freezing cycles usually only one type of ice was produced. On the undisturbed samples, however, needle-ice crystals grew discontinuously on the soil surface, there was a large range of crystal lengths, and a wide variety of types of needle ice were grown during one freezing cycle. The difference in needle-ice characteristics between the sample types are thought to be a result of the effect of soil disturbance on the grain-size distribution of the soil. Remoulding the soil eliminated differences in the particle-size distribution on the soil surface, and thus produced a uniform surface for needle-ice growth. Undisturbed samples, however, had small-scale differences in grain-size composition on the soil surface.

10.4.2 Needle-ice growth

Despite suggestions reported in Chapter 2 that the process of needle-ice growth is well understood and well documented, a large part of this study has focused upon the processes by which needle-ice crystals grow. The incorporation of hitherto neglected instrumentation into the experiment (such as displacement transducers and moisture elements) has provided new information about the processes of needle-ice growth.

It was suggested that moisture is the most important factor which determines first, whether at appropriate soil-surface temperatures, needle ice grows at all, second, the type of needle ice and third, the rate of crystal growth. This is because the soil-moisture content not only provides a source of water to the growing needles, but also controls the thermal properties of the soil. Other factors which influence needle-ice growth include the cooling rate of the soil surface (which should be slow, ideally 0.5°C to 1.5°C h^{-1}) and final soil-surface temperature.

The study has also explored the conditions associated with the temporary or permanent cessation of needle-ice growth. Disturbance to the growth environment, which is caused when the heat flux equation becomes unbalanced (as a result of low soil-moisture content and/or temperatures), has been shown to result in the incorporation of sediment into the crystals.

10.4.3 Sediment incorporation into needle ice

Different types of spatial and temporal variability of disturbance to growth resulted in the formation of different types of needle ice and varying patterns and amounts of sediment inclusion. It appears that moisture content is the main factor that controls sediment inclusion. If the flow of moisture to the freezing front is sufficient then most disturbances to temperature can be accounted for by soil-moisture migration. If soil moisture is limited, however, ice segregation ceases. It was found that the freezing front then descends into the soil profile, causing in-situ freezing, and a layer of sediment is then incorporated underneath the needle-ice crystals, in the manner envisaged by Fukuda (1936), Hay (1936), Soons and Greenland (1970) and Outcalt (1971a). Once ice segregation recommences the soil appears as a distinct layer in the needle-ice crystals.

This area of analysis is important in two respects; first, because it gives an indication of the growth history of the ice needles, and secondly in a geomorphological context, because, as shown in Chapters 1 and 3, needle ice grows throughout most of the world and the lifting of sediment by the crystals is common.

It was found that different types of sediment lift and incorporation occurred as a result of different types of limitations to the environment of needle-ice growth. Sediment was included as well-defined, distinct layers or distributed throughout the crystal. It was also lifted as a cap on top of the needles, or as aggregates lifted between dispersed needle-ice crystals. The type of sediment inclusion that occurs appears to depend on the nature of the disturbance to growth. Soil caps, although they were produced in less than 10% of experiments, were responsible for c.85% of the total sediment yield caused by needle-ice growth in this study. A new terminology has been introduced that aims to clarify the confusion when describing crystals that grow during one freezing cycle and those that grow over several freezing cycles.

There was selective entrainment of coarser particles into the needle-ice crystals, unlike the results of the experiments of Meentemeyer and Zippin (1980). This is an important observation, and may explain why, in many areas, needle-ice has been considered as a factor that causes sorting of material. Preferential sorting by needle ice in this study is thought to occur during periods of freezing front descent when coarse particles become frozen into the pore ice, whilst many finer particles are pushed ahead of the freezing front and are thus less likely to be incorporated into the ice. In this area of analysis parallels have been drawn between the processes which occur during needle-ice growth and those which occur during the development of ice lenses and other types of frozen soil.

10.4.4 Sediment transport by needle ice

The incorporation of sediment into the needle ice is the first stage in the process of soil erosion by needle ice. The second stage is the transport of sediment downslope, and the present study has provided perhaps the most detailed research on sediment transport by needle ice undertaken in a laboratory.

Previous studies have modelled sediment transport entirely on the basis of slope angle and crystal length. The results of this study show this to be an oversimplification of the process, and the distance of transport was shown to depend on a greater number of variables, including slope angle, soil type, crystal length, type of marker particle and process of melt.

The processes by which ice needles melt have been largely neglected in the literature, and the link between needle-ice melt and sediment transport had not been fully explored. In this study it was found that the process of melt itself is influenced by soil type, soil-surface temperature and the amount of sediment within the ice crystal. Crystals usually melted by one of three processes: toppling, gradual melt or a combination of the fracture and melt. Most of the general geomorphology and periglacial literature state that the needles topple, and thus sediment is transported in the manner described in the gravity-fall model, which is the model used most frequently to predict sediment displacements. Toppling, which usually occurred on the undisturbed samples, caused sediment to be transported the greatest distance downslope.

10.4.5 Modelling the growth and morphological effects of needle-ice growth

The growth of needle ice and the erosion of sediment as a result of needle-ice growth was represented as a series of semi-empirical statistical models. First, the length of needle-ice crystal that will grow in a given freezing cycle was predicted. The model used the moisture content of the soil surface immediately prior to freezing and an index termed 'segregation time'. Segregation time is the duration of sub-zero temperatures above a minimum temperature threshold after ice nucleation occurred (the minimum threshold depended on the soil-moisture content). This new form of model predicted the length of needle ice more accurately than models which use only the duration of temperatures below a given threshold. (The latter model had an R^2 of 10.2% and a standard error of 7.75 mm whereas the new model increased the R^2 to 64.7% and reduced the standard error to 4.9 mm.) It was also possible to predict pattern of needle-ice growth in a freezing cycle, given information on the rate of change of soil-moisture content just below the soil surface, although the rate of growth was usually under- or over-estimated.

In the second stage of modelling an attempt was made to determine the amount of sediment that is incorporated during needle-ice growth. Previous models, based on field data have used only the length of needle-ice crystal to predict sediment yield. This approach was found to be inadequate for the laboratory study, however, because it does not take into account the effects of moisture and temperature fluctuations which have been found to influence sediment incorporation. A new model of sediment incorporation was therefore developed which included soil moisture and temperature variables as well as length. The model assumes that sediment incorporation occurs when soil-moisture and temperature drops below a certain threshold and causes needle-ice growth to cease. This model predicted sediment yield more accurately than the sediment yield/length model. The most accurate method to predict sediment yield however, was when a separate equation was used for each type of ice crystal. For multitiered and dispersed-sediment crystals, length has the greatest influence on sediment yield, whilst for soil caps the moisture content at the soil surface is more important. The sediment yield from aggregates was closely related to the amount of ice that grew on the soil surface.

Finally, the distance of sediment transport was modelled. The actual distance of transport in the study and the amount predicted by existing transport models were compared. This comparison revealed that both the length of needle ice and the slope angle are important for determining the distance of transport. Indeed, slope seemed to have a greater influence on sediment transport than has been indicated in the gravity-fall and Higashi and Corte models. In a new semi-empirical model, transport distance was made a function of the length of needle-ice crystal (modified if the sediment was included within the crystal), and Θ, the coefficient of slope angle. The new model of transport predicted distances more precisely than existing models, although it was only possible to test it for situations where the sediment rested on top of the ice crystal, not for sediment within the crystal.

10.4.6 Summary of main findings

i) improvement and extension of techniques used to simulate the growth of needle ice and the transport of sediment in the laboratory. The continuous monitoring of needle-ice heave, temperature and soil-moisture was particularly successful. These techniques may now be used in field experiments;

ii) the effects of soil disturbance on needle-ice growth, sediment incorporation and transport have been identified;

iii) a new terminology to describe sediment inclusion in needle ice has been developed;

iv) several patterns of needle-ice growth have been identified, and their occurrence related to fluctuations in soil-moisture content and temperature

v) the theories of Fukuda (1936), Outcalt (1971a) and others regarding the incorporation of sediment layers into needle ice have been tested and verified;

vi) the selective entrainment of coarse particles into needle ice has been identified and an attempt made to explain the process;

vii) three mechanisms of needle-ice melt have been identified and linked to the distance of sediment transport;

viii) the effects of needle-ice height, slope angle and soil and marker type on the distance of sediment transport have been determined;

ix) an algorithm to predict the type of needle ice that will grow in a given freezing environment has been developed and tested;

x) simple statistical models have been developed to predict the growth and morphological effects of needle ice.

Appendix 1

SUMMARY OF NOTATION

a	distance of lateral sediment transport
a_h	distance of lateral sediment transport per unit of crystal length
a_l	distance of lateral sediment transport to left of the sample box
a_r	distance of lateral sediment transport to right of the sample box
A	area of sample; advection
C	weight of container
c_s	volumetric heat capacity of soil
c_w	volumetric heat capacity of water
d	distance of downslope movement
d_a	actual distance of downslope movement
d_h	distance of downslope movement per unit of crystal length
d_i	distance from nearest edge of sample box
d_p	predicted downslope movement
d_u	distance of upslope movement
D	distance of LVDT movement
D_C	duration below minimum threshold temperature for ice segregation
D_N	duration of sub-zero temperatures after ice nucleation
D_s	segregation time
DSB	remoulded soil samples from the Bournbrook site
DSE	remoulded soil samples from the Edgbaston site
D_0	duration of soil-surface temperatures < 0°C
$D_{1.5}$	duration of soil-surface temperatures < -1.5°C

D_5	duration of soil-surface temperature < -5°C
e	coefficient to represent the location of sediment within the ice crystal
E	latent heat flux; evaporation; sediment yield
E_c	sediment yield per unit crystal length
h	length of needle ice
h_a	actual length of needle ice
h_p	predicted length of needle ice
H	sensible heat flux
k	coefficient of adhesion
K↓	incoming short-wave radiation
K↑	outgoing short-wave radiation
K^*	net short-wave radiation
L	latent heat
L_s	distance between top of soil layer and top of ice crystal
LV	output of LVDT
LVDT	linear displacement transducer
L↓	incoming long-wave radiation
L↑	outgoing long-wave radiation
L^*	net long-wave radiation
M	moisture content
M_s	soil-surface moisture content
M_{sa}	soil-surface moisture content after experiment
M_{sb}	soil-surface moisture content before experiment
M_1	moisture content 1 cm below the soil surface
M_3	moisture content 3 cm below the soil surface
M_5	moisture content 3 cm below the soil surface
M_{10}	moisture content lagged by 10 minutes

M_{70}	moisture content lagged by 70 minutes
p	precipitation
P	output of platinum resistance thermometer
P_0	output of platinum resistance thermometer at 0°C
Q_E	latent heat
Q_G	conduction
Q_H	sensible heat
Q_P	net energy stored by photosynthesis
Q_S	storage of heat in atmosphere and ground
Q^*	net all-wave radiation flux
r	pore radius
R	cooling rate
S	slope angle
SS	sum of squares
t	time
T	temperature
T_a	actual temperature
T_N	nucleation temperature
T_r	required temperature
T_s	soil surface temperature
T_{sky}	sky temperature
T_0	freezing point of water; surface temperature
T_1	soil temperature 1 cm below the soil surface
T_3	soil temperature 3 cm below the soil surface
USB	undisturbed soil sample from the Bournbrook site
U_w	soil water flux velocity
V	voltage

W_d	weight of dry soil
W_w	weight of wet soil
Y_i	ice yield
Z	depth
α	albedo
Δh	change in needle-ice length
ΔM	change in soil moisture content
ΔM_1	change in soil moisture content 1 cm below the soil surface
ΔM_{10}	change in soil moisture content lagged by 10 minutes
ΔM_{70}	change in soil moisture content lagged by 70 minutes
Δr	change in runoff
ΔS	change in storage; change in soil-moisture content
ΔT_s	change in soil-surface temperature
γ_{crit}	critical water content
θ	coefficient of slope angle
κ	soil thermal diffusivity
σ	Stefan-Boltzmann constant
σ_{iw}	interfacial energy between ice and water

Appendix 2

DETAILS OF EXPERIMENTAL APPARATUS

Equipment	Part Number	Accuracy / Stability	Supplier
Grant Instruments YSI mini-thermistors	CM-U	accuracy ± 0.2°C drift ± 0.015°C	Grant Instruments (Cambridge) Ltd, Barrington, Cambridge, CB2 5Q2.
Platinum resistance probes	PT100/15A	PT 100 sensor, 100 Ohms at 0°C to BS 1904	Sensing Devices Ltd, 97, Tithebarn Rd, Southport, Merseyside, PR8 6AG.
Eijkelkamp soil moisture elements	14.23.04	No data available	Van Walt Ltd, Prestwick Lane, Grayswood, Haslemere, Surrey, GU27 2DU
Linear variable displacement transducers	NDL/25mm/SDG	accuracy 0.3%	Sangamo Weston Controls Ltd, North Bersted, Bognor Regis, Sussex, PO22 9BS.
BBC Microcomputer		resolution 12 bit	Not presently available
Grant Instruments 1200 Series Squirrel Datalogger	1207	resolution 1 bit (0.4% span) accuracy ± bit	As for thermistors
Various electrical components			R.S. Components, P.O Box 253, Duddleston Mill Industrial Estate, Saltley, B81 1BQ

Appendix 3

EXAMPLE OF EXPERIMENTAL CONTROL PROGRAMME

```
10   REM **** NEEDLE ICE COOLING CURVE ****
20   REM *********** JB 1990 **************
30   MODE 1
40   VDU 19,2,11,0,0,0
50   REM ** VARIABLES FOR ADVAL TO TEMP CONVERSION **
140  X = 0
150  ?&FE62=&FF
160  DIM TEMP(144)
170  DIM ACT(144,4)
180  DIM CURT(4)
190  DIM X(4)
200  REM
210  REM  ******* REQUIRED COOLING CURVE *******
220  REM
230  FOR G=1 TO 48
240          READ TEMP(G)
250  NEXT G
260  FOR G=49 TO 66:TEMP(G) = -1.5
270  NEXT G
280  TEMP(67)=-2.5:TEMP(68)=-2.5
290  FORG=69 TO 90:TEMP(G) = -1.5
300  NEXT G
310  TEMP(91)=-2.5:TEMP(92)=-2.5
320  FOR G =94 TO 133:TEMP(G)=1.5
330  NEXT G
340  @%=&2020A
350  REM
360  REM *** WAIT FOR COOLING CHAMBER TO COOL DOWN ***
370  REM
380  TIME=0
390  PRINT TAB(5,15) "Fridge cooling down prior to run"
400  REQT=3
410  REPEAT
420          PROCGETTEMP
430          IF CURT(2) >REQT THEN PRINTTAB(25,27);"                    "?&FE60=255
440          IF CURT(2) >REQT THEN PRINTTAB(25,27);"HEATING COIL ON "    ?&FE60=255
450          @%=&2020A
460          PRINTTAB(12,20) CURT(2)
470          @%=%10
480          SEC=(TIME DIV 100) MOD 60
490          MIN=(TIME DIV 6000) MOD 60
500          HR=(TIME DIV 360000)
510          PRINTTAB(0,0) HR;":";MIN;":"SEC
520  REPEAT UNTIL TIME MOD 2000=0
530  UNTIL TIME DIV 3600000 = 1
540  @%=&2020A
550  CLS
```

```
560  REM
570  REM **** GRAPH ****
580  REM
590  PRINTTAB(2,1);"                    Required Surface Temperature"
600  PRINTTAB(2,2);"                    ________________________________"
610  PRINTTAB(30,16);"       t "
620  PRINTTAB(0,2);T"
630  PLOT 4,5,500:DRAW 1100,500:PLOT 4,5,100:DRAW 5,900
640  FOR G=1 TO 144
650          PLOT 69, (G*7)+5,500+(100*TEMP(G))
660  NEXTG
670  REM
680  REM **** MAIN LOOP ****
690  REM
700  TIME=0
710  FOR T = 1 TO 144
720          REQT=TEMP(T)
730          REPEAT
740             PROCGETTEMP
750          IF CURT(2) >REQT THEN PRINTTAB(25,27);"                  "?&FE60=255
760          IF CURT(2) >REQT THEN PRINTTAB(25,27);"HEATING COIL ON      ":?&FE60=0
770          PROCDISPLAY
780          UNTIL (TIME/6E4)>T
790          PROCOPTEMPS
800  NEXTT
810  PROCtodisc
820  END
830  DATA 2.8, 2.67, 2.5, 2.33, 2.17, 2, 1.83, 1.67, 1.5, 1.33, 1.17, 1, 0.92, 0.83, 0.75, 0.67, 0.58, 0.5,
     0.42, 0.33, 0.25, 0.17, 0.08, 0,
840  DATA -0.06, -0.12, -0.18, -0.23, -0.29, -0.35, -0.4, -0.45, -0.5, -0.55, -0.62, -0.68, -0.75, -0.82,
     -0.88, -0.93, -1.02, -1.08
850  DATA -1.15, -1.21, -1.27, -1.33, -1.38, -1.44, -1.5
860  REM
870  REM **** DETERMINING CURRENT TEMP ****
880  DEF PROCGETTEMP
890  X(1)=0:X(2)=0:X(3)=0:X(4)=0
900  FOR I = 1 TO 50
910  X(2)=X(2) + ADVAL(1) DIV 16
940  NEXT I
950  X(2)=X(2)/50
980  CURT(2)=(X(2)-1410) DIV 132.1
1010 ENDPROC
1020 REM
1030 REM **** DISPLAY CURRENT TEMP ****
1040 DEF PROCDISPLAY
1070 PRINTTAB(7,6);"current temp.       required temp."
1080 PRINTTAB(10,5);CURT(2),REQT
1090 GCOL 0,2
1100 PLOT 69, (T*7)+5,500+100*CURT(2)
1110 REPEAT UNTIL TIME MOD 1000=0
1120 PLOT 71,(T*7)+5,500+100*CURT(2)
1130 GCOL 0,3
1140 ENDPROC
1150 REM
1160 DEF PROCOPTEMPS
```

```
1170 REM **** OUTPUTTING DATA ****
1180 ACT(T,2)=CURT(2)
1210 ENDPROC
1220 REM
1230 DECPROCtodisc
1240 Y=OPENOUT("ACT")
1250 FOR G = 1 TO 144
1260         PRINT#Y,ACT(G,2)
1290 NEXTG
1300 CLOSE#Y
1310 ENDPROC
```

Appendix 4

SUMMARY OF NEEDLE-ICE GROWTH AND SEDIMENT INCORPORATION EXPERIMENTS

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
P_1	DSE_1	A	12	28.0	0.133	C	3.0	0.017
P_2	DSE_1	A	12	39.0	0.330	C	5.0	0.02
P_3 *	DSE_1	F	24	68.0	0.00	N	0	0.00
P_4	DSE_1	B	24	62.0	17.00	C	20.0	0.03
P_5	DSE_1	C	30	33.8	25.00	A	15.0	1.41
P_6	DSE_1	D	24	35.0	17.00	D	36.0	1.40
P_7	DSE_1	D	12	34.3	11.00	D	17.0	0.50
P_8	DSE_1	E	12	59.8	7.00	C	10.0	0.09
P_9	DSE_1	E	24	40.0	19.00	M	19.0	0.19
P_{10}	DSE_1	E	24	65.0	11.00	M	16.0	0.20
P_{11}	DSE_1	B	24	55.0	19.00	D	36.0	0.60
P_{12}	DSE_1	B	12	70.0	8.00	C	22.0	0.32
P_{13}	DSE_1	E	24	41.0	19.00	M	26.0	0.19
P_{14}	DSE_1	A	12	25.0	1.50	N	0	0

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
P_{15}	DSE_1	A	30	54.0	19.80	C	25.0	0.12
P_{16}	DSE_1	D	24	26.0	13.00	N	0	0.00
P_{17}	DSE_1	D	30	56.0	17.00	C	40.0	0.08
P_{18}	DSE_1	D	24	50.0	20.00	D	26.0	1.38
P_{19}	DSE_1	D	24	63.0	0.67	N	0	0
10/1/90 *	DSE_1	F	16	13	14.00	N	0	0
23/1/90 *	USB_1	F	20	5.0	16.00	N	0	0
1/11/90	DSE_1	E	24	59.0	22.00	C	35.0	1.41
2/11/90	DSE_1	B	12	10.0	0.00	N	0	0.00
5/11/90	DSE_1	E	25	42.0	10.33	M	26.0	0.22
6/11/90	DSE_1	B	12	35.0	7.00	C	4.0	
7/11/90	DSE_1	A	12	42.0	2.83	A	9.0	0.36
8/11/90 *	USB_1	E	22	23.0	21.00	S	17.5	0.15
9/11/90	USB_1	A	21	35.0	10.00	D	10.0	
13/11/90 *	USB_1	E	20	40.0	6.50	M	5.5	
14/11/90	DSE_2	E	24	30.0	5.50	M	7.5	0.03
15/11/90	DSE_2	F	24	35.0	10.50	D	9.0	
19/11/90	DSE_2	F	24	48.0	11.50	C	10.0	0.02
21/11/90	DSE_2	F	24	40.0	11.50	D	9.0	0.20

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
22/11/90	DSE_2	F	12	64.0	1.80	D	20.0	
23/11/90 *	DSE_1	D	17	34.0	10.00	C	17.0	0.31
24/11/90	USB_1	D	24	74.0	18.00	A	17.0	1.20
27/11/90 *	USB_1	D	24	12.0	18.00	S	8.5	0.20
29/11/90	USB_1	D	24	59.0	19.00	D	21.0	0.31
30/11/90	USB_1	F	20	34.0	1.00	M	17.0	0.18
1/12/90	USB_1	D	24	52.4	16.00	D	25.0	0.66
3/12/90	USB_1	F	20	34.0	8.00	D	11.0	0.26
4/12/90 *	USB_1	D	9	21.0	0.50	N	0	0
5/12/90 *	USB_1	D	12	23	2.00	N	0.0	0.00
10/12/90	USB_1	B	24	40.0	9.50	M	10.0	0.16
11/12/90	USB_1	B	12	41.0	9.10	C	2.5	
12/12/90	USB_1	A	12	70.0	0.67	N	0	0.00
14/12/90	DSB_1	C	16	28.0	1.12	D	3	
15/12/90	DSB_1	D	24	28.0	0.90	D	3	
17/12/90	DSB_1	C	18	27.0	2.00	N	0	0.00
6/1/91	DSB_1	E	24	27.9	4.00	M	3	0.99
10/1/91	DSB_1	F	24	35.0	1.49	N	0	0.00
11/1/91 *	USB_1	E	24	29.5	14.00	M	12	0.03

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
12/1/91	USB_1	F	24	23.4	10.67	D	6	
23/1/91	USB_1	A	11	42.0	3.50	S	6	0.01
24/1/91	USB_1	F	24	42.0	0.50	C	7	
28/1/91	USB_1	C	16	44.0	4.00	M	28	0.18
29/1/91	USB_1	F	24	45.0	14.00	C	13	
30/1/91	USB_1	D	24	30.0	5.00	M	5	
1/2/91	USB_1	B	19	40.1	0.00	N	0	
2/2/91	USB_1	C	30	48.0	23.00	C	35	0.08
3/2/91 *	USB_2	C	35	45.0	10.83	M	26	0.26
4/2/91	DSB_1	F	24	49.0	13.00	C	35	
5/2/91	DSB_1	F	24	44.0	10.00	A	25	2.10
6/2/91	DSB_1	D	38	27.0	3.00	D	2	0.02
7/2/91	DSB_1	D	24	38.0	10.00	C	7	
8/2/91	DSB_1	F	24	45.0	10.30	C	10	
10/2/91	DSB_1	F	24	28.6	3.00	S	7	
11/2/91 *	USB_1	D	24	43.0	4.50	M	7	0.12
12/2/91	USB_1	C	12	38.6	7.00	C	7	0.03
13/2/91	USB_1	C	12	53.0	3.00	D	20	0.18
14/2/91	USB_1	C	12	52.6	0.50	A	15	

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
19/2/91	USB_1	F	24	53.0	11.30	M	19	0.94
20/2/91	USB_1	F	24	56.9	10.00	A	25	2.45
25/2/91	USB_1	F	24	67.8	10.00	M	21	0.25
1/3/91	USB_1	F	24	67.8	2.17	M	11	0.18
11/3/91	USB_1	F	24	52.0	6.50	D	13	0.26
14/3/91 *	USB_1	D	24	32.0	6.00	M	11	0.15
18/3/91 *	USB_1	E	21	31.0	15.00	M	19	0.02
19/3/91	DSB_1	E	8	24.0	11.67	S	19	1.16
20/3/91 *	DSB_1	E	24	37.0	11.70	D	24	0.15
21/3/91 *	USB_1	D	25	34.0	21.00	C	13	0.04
22/3/91 *	USB_1	F	24	55.0	19.00	C	12.7	
23/3/91	DSB_1	F	24	29.0	8.00	D	5.5	
8/4/91	DSB_1	E	24	39.0	11.50	M	21	0.18
9/4/91	DSB_1	F	24	32.0	0.34	A	26	2.19
10/4/91	DSB_1	F	24	29.0	6.00	A	5.5	
1/7/91	DSB_1	C	12	31.5	1.63	D	27	0.60
2/7/91	DSB_1	E	18	30.0	2.17	M	9	0.30
3/7/91 *	USB_1	F	29	26.0	24.00	D	9	
8/7/91 *	USB_1	D	18	31.0	2.00	D	44	1.20

Expt		Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
9/7/91	*	USB_2	F	12	37.0	10.00	M	9	
10/7/91	*	USB_1	D	17	55.0	14.00	M	15	
11/7/91	*	USB_1	E	20	40.0	13.00	M	12	
15/7/91		DSB_1	C	20	45.0	7.00	D	14	0.4
16/7/91		DSB_1	C	20	45.0	8.00	D	10	
17/7/91		DSB_1	C	24	20.0	2.30	S	42	1.2
18/7/91		DSB_1	C	20	24.0	3.00	S	41	0.8
23/7/91		DSB_1	C	12	44.0	1.30	S	3	0.19
12/9/91		USB_2	F	24	49.0	9.33	C	41	0.08
13/9/91		USB_2	F	15	37.0	3.00	D	7	0.17
30/9/91		DSB_1	F	20	38.0	0.80	S	3	0.16
3/10/91		DSB_1	D	24	45.0	4.00	C	9	0.02
6/10/91		DSB_1	F	24	41.0	9.00	C	9	0.09
7/10/91		DSB_1	E	24	33.0	15.00	M	10	0.15
8/10/91		DSB_1	C	12	47.0	8.00	M	15	0.15
9/10/91		USB_1	C	12	43.0	2.67	A	46	0.46
11/10/91		USB_1	C	12	34.0	4.50	D	17	0.43
22/10/91		USB_1	F	24	31.0	4.50	A	15	1.50
23/10/91		USB_1	B	12	33.0	4.50	M	10	0.15

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment (g cm^{-2})
6/11/91	USB_1	E	24	27.9	4.00	M	5	0.35
11/11/91	USB_1	F	24	32.0	5.00	D	5	0.20
12/11/91	USB_2	F	24	29.0	10.17	A	14	0.68
13/11/91	USB_2	F	24	32.0	16.17	A	17	0.70
14/11/91	USB_2	F	24	34.0	0.50	N	0	0.00
23/11/91	USB_2	F	24	34.0	0.70	N	0	0.00
25/11/91	DSB_1	F	24	35.0	9.50	D	10	0.40
26/11/91	USB_2	F	24	37.0	9.50	D	9	0.29
29/11/91	DSB_2	F	24	65.0	16.00	C	21	0.16
3/12/91	DSB_2	F	24	28.8	13.00	D	15	
8/12/91	DSB_2	F	24	54.0	14.00	D	20	1.19
9/12/91	DSB_2	C	12	54.0	10.00	C	15	0.43
10/12/91	USB_2	C	12	54.0	7.00	A	25	2.10
12/12/91	USB_2	C	12	44.0	4.50	S	2	0.19
15/12/91	USB_2	C	12	28.0	9.50	D	6	
16/12/91	USB_2	C	30	32.0	5.00	D	3	0.05
3/1/92	USB_2	C	12	27.0	8.00	M	13	1.38
5/1/92	USB_2	C	12	35.0	7.67	D	5	0.19
6/1/92	USB_2	C	12	35.0	4.67	C	4	0.02

Expt	Sample	Curve	Duration (hours)	M_s (%)	D_s (hours)	Needle type	Length (mm)	Sediment ($g\ cm^{-2}$)
13/1/92	USB_2	D	24	33.0	9.00	D	34	0.18
15/1/92	USB_2	D	24	33.6	11.00	D	11	0.18
16/1/92	USB_2	E	24	33.6	11.00	D	38	0.58
17/1/92	USB_2	D	15	29.0	3.00	D	30	0.91
20/1/92	USB_2	E	20	42.0	12.50	D	17	0.50
27/1/92	USB_2	D	24	32.0	6.00	D	14	
28/1/92	USB_2	B	12	27.0	4.00	N	0	0
6/3/92	USB_2	F	24	32.0	8.0	D	5	
19/3/92	USB_2	F	24	21.0	2.30	S	27	0.49
20/3/92	USB_2	E	12	29.0	10.00	D	27	0.49
21/3/92	USB_2	C	12	26.0	9.20	D	15	0.35

Notes:

* : denotes experiment discussed in the thesis

Sample : see section 5.2.1 and Figures 5.2 and 5.3
DSE - disturbed sample, garden site
DSB - disturbed sample, river-bank site
USB - undisturbed sample, river-bank site

Curve : see Section 5.3.1 and Figures 5.9 and 5.10

M_s : moisture content at soil surface before experiment

D_s : segregation time (see Section 9.2)

Crystal type : main type produced during the experiment

- **A** - sediment aggregates lifted
- **C** - clear crystals
- **D** - crystals with dispersed sediment
- **M** - multitiered crystals
- **S** - soil cap

Length and **sediment yield,** data based on the mean of 10 needles randomly selected from the soil surface (see Section 5.4)

Appendix 5

SUMMARY OF SEDIMENT TRANSPORT EXPERIMENTS

Expt.	Sample	Slope (°)	Marker	Length[a] (mm)	Downslope movement[a] (mm)	Lateral movement[a] (mm)
6/3/92	USB_2	5	N	7	6.55	4.59
9/3/92	USB_2	5	N	4	2.33	-0.20
10/3/92	USB_2	5	N	5	4.00	1.33
12/3/92	USB_2	5	N	4	2.30	-0.22
17/3/92	USB_2	5	N	3	-4.00	1.44
18/3/92	USB_2	5	N	2	-0.11	1.33
12/12/91	USB_2	6	N	4	3.06	1.12
15/12/91	USB_2	6	N	4	2.31	0.25
20/12/91	USB_2	6	N	6	2.60	0.82
2/1/92	USB_2	6	N	4	0.40	2.20
3/1/92	USB_2	6	N	5	3.90	0.67
6/1/92	USB_2	10	N	9	8.95	0.25
13/1/92	USB_2	10	N	4	2.15	2.06
15/1/92	USB_2	10	N	3	1.41	-0.56
19/2/92	DSB_2	15	N	4	2.00	0.81
20/2/92	DSB_2	15	N	7	4.51	0.50
22/2/92	DSB_2	15	N	12	9.40	1.30
24/2/92	DSB_2	15	N	9	6.13	0.99
27/1/92	USB_2	15	N	5	3.69	0.56
28/1/92	USB_2	15	N	6	2.81	0.50
30/1/92	USB_2	15	N	4	1.56	0.06
10/2/92	USB_2	15	N	6	1.06	0.31
25/2/92	USB_2	15	C	11	15.00	0.05
26/2/92	USB_2	15	C	1	1.75	-0.67
27/2/92	USB_2	15	C	5	4.20	0.01

Expt.	Sample	Slope (°)	Marker	Length[a] (mm)	Downslope movement[a] (mm)	Lateral movement[a] (mm)
2/3/92	USB_2	15	C	2	1.33	-0.25
19/2/92	USB_2	15	S	8	6.31	0.94
20/2/92	USB_2	15	S	9	6.31	-0.80
22/2/92	USB_2	15	S	4	12.00	0.80
24/2/92	USB_2	15	S	2	7.40	1.00
2/12/91	USB_2	22	N	7	5.33	0.58
3/12/91	USB_2	22	N	3	2.06	2.50
9/12/91	USB_2	22	N	10	9.00	0.84
10/12/91	USB_2	22	N	5	6.30	0.25
6/3/92	DSB_2	30	N	3	2.25	-0.25
9/3/92	DSB_2	30	N	2	1.25	0.83
10/3/92	DSB_2	30	N	7	6.70	0.50
12/3/92	USB_2	30	N	10	10.17	-0.58
17/3/92	USB_2	30	N	2	4.33	-0.08
18/3/92	USB_2	30	N	4	3.42	0.58
30/3/92	USB_2	30	N	7	7.33	-1.25

[a] represents the mean movement of 16 markers

N : natural stones
S : spheres
C : cubes

Appendix 6

The Laboratory Simulation of Needle Ice

Julia Branson*, Damian M. Lawler* and John W. Glen**

* School of Geography, University of Birmingham, Birmingham, B15 2TT, United Kingdom
** School of Physics and Space Research, University of Birmingham, Birmingham, B15 2TT, United Kingdom

ABSTRACT : Needle ice is a small-scale form of ground ice that grows at the soil surface when moist frost-susceptible soils are subjected to freezing and thawing conditions. This paper discusses an investigation into needle-ice growth and the disturbance of sediment by needle ice, based on a series of detailed laboratory experiments. The preliminary results show that needle ice can grow in experiments with 'smooth' or 'intermittent' growth rates. It is suggested that intermittent growth occurs when there is disturbance to the soil-moisture or heat flux. The lifting of material by needle ice is also discussed. This sediment lift is important because it both gives an indication of the growth history of the needle ice and also can give rise to appreciable soil erosion.

1 INTRODUCTION

Needle ice (pipkrake, kammeis, shimobashira) is a term used to describe columnar ice crystals, which range in length from a few millimetres to several centimetres (Figure 1). Needle ice is a small-scale form of frost heave, produced by ice segregation (1,2) from a stable freezing front at, or just below, the ground surface. The growth of needle ice is usually associated with diurnal freeze-thaw conditions affecting loamy soils or plant materials with a sufficient moisture supply.

The requirements for needle-ice growth can be summarised as follows (3):

i) A soil-surface temperature low enough to supercool the moisture at the soil surface (approximately -2°C).
ii) Sufficient soil moisture to allow ice segregation to begin.
iii) A fast flow of water bringing sufficient heat to the freezing front to balance the heat loss at the soil surface (this ensures that the freezing front is stable).

Other conditions also need to be met for needle-ice growth to occur, some of which are related to the chemical and physical properties of the soil. For example, Fukuda (4) stated that for needle ice to grow it is necessary to have some colloids in the soil that adhere to the sand grains. The colloids help retain moisture in the soil. When quartz sand was washed with water, Fukuda observed that no needle ice grew. Too much colloid, however, was also thought to be detrimental to needle-ice growth because the passage of water in the soil would be impeded.

The process of needle-ice growth is thought to be similar to that of the fibrous forms of gypsum, common salt etc. (5). These fibres grow at their bases and are thus pushed upwards out of the growth medium. The growth of the fibres cannot be stopped by insulating their tops. Steinemann (5) argued that evidence to support this hypothesis of growth for needle ice includes the lateral dimensions of the crystals, which approximate the inter-pore distances of the soil. By analysis of thin sections of needle-ice crystals Steinemann determined that their optic axis was perpendicular to the direction of growth, and thus to the temperature gradient.

The growth requirements of needle ice are met throughout the world in alpine, sub-alpine, arctic and temperate environments (6,7). Needle-ice growth is most prolific in alpine areas such as the Venezuelan Andes where needle ice has been reported to grow 325 to 350 times/year (8).

Despite there being much work concerned with the micrometerological and soil moisture controls on

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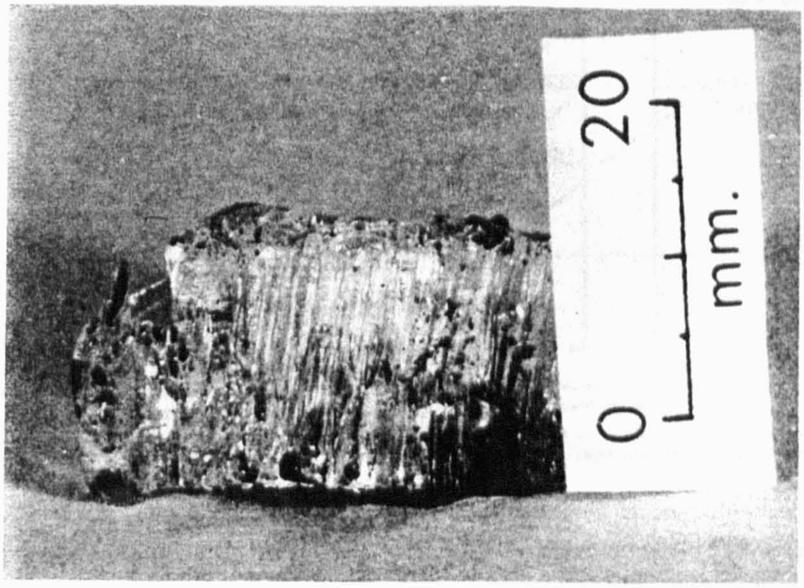

Figure 1: Needle ice

needle-ice growth, little is known about the effect which changing soil-moisture content and temperature during a freezing cycle have on growth. The research reported in this paper investigates how needle-ice growth responds to disturbances in the growth environment. The work is part of a wider laboratory investigation into needle-ice growth and sediment disruption by needle ice.

2 EXPERIMENTAL DESIGN

The apparatus used for the experiments is shown in Figure 2. The rationale behind the design was to allow the control of several factors that are thought to influence the process of needle-ice growth, and to assess their relative importance to the mechanisms of soil disturbance by needle ice.

The experiments mainly used undisturbed soil samples that were taken from a river bank where needle ice was observed to grow naturally. Most other laboratory studies of needle ice have used disturbed (remoulded) samples (e.g. (9,10,11)). This may cause problems as remoulding the soil may affect its frost susceptibility.

The bottom half of the soil sample box contained a water reservoir that provided a supply of water to the base of the soil. Temperature was measured at the soil surface and within the soil profile with platinum resistance probes. Soil-moisture content within the soil was monitored using nylon soil-moisture elements. Heave at the soil surface was continuously measured by two linear displacement transducers. The apparatus was placed into a small cold chamber and subjected to one of several preprogrammed cooling curves. As needle ice was successfully grown in a laboratory situation it appears that radiative cooling is not essential for ice segregation to occur.

The temperature probe at the soil surface was used with a microcomputer and heating coil to control soil-surface temperature. In this respect the study varied from most other needle-ice experiments, where changes in temperature were controlled manually. Several cooling curves were programmed into the computer so that the sample would be cooled at different cooling rates. The heater was switched on when the soil-surface temperature (monitored every ten seconds) fell below that determined by the computer programme. Experiments typically lasted between 12 and 24 hours and the output variables were recorded every 10 minutes by a datalogger.

A more detailed discussion of the experimental design is given in (12).

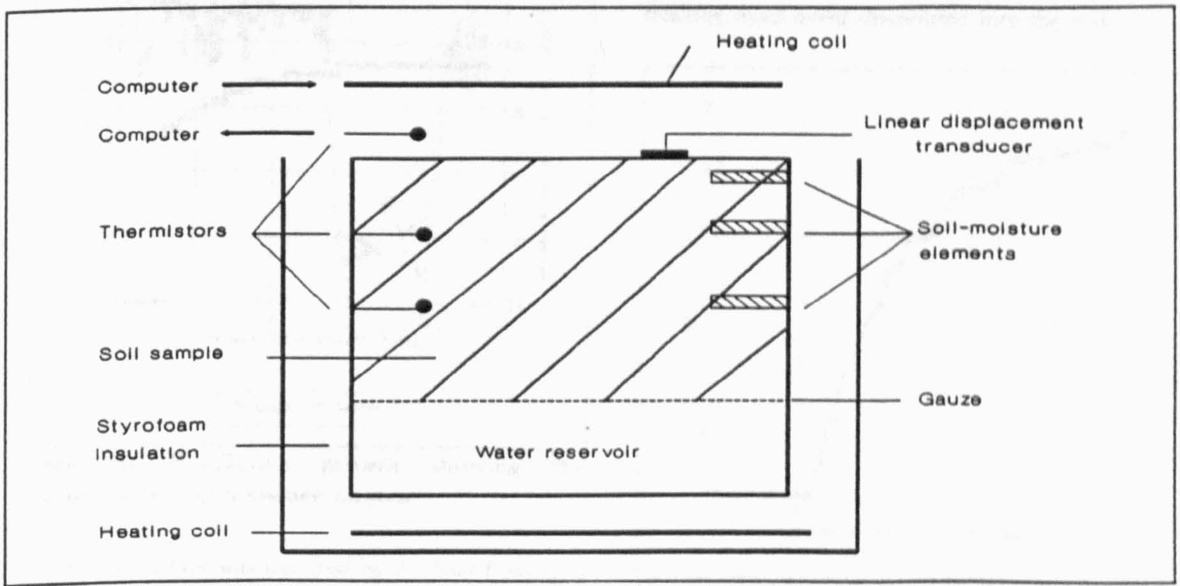

Figure 2: Schematic diagram of the needle-ice experiment (soil sample measures 30cm x 30cm x 20cm)

3 NEEDLE-ICE GROWTH

Needle-ice growth was continuously monitored through freezing and thawing cycles. The profiles produced give information about the changing rate of needle-ice growth through given cooling sequences.

3.1 The rate of needle-ice growth

The rate of needle-ice growth was typically non-linear, with a very high initial growth rate after which the rate of growth usually decreased with time.

The initial high rate of growth just after ice nucleation may be related to the supercooling of the water in the soil. As the soil-surface temperature decreases, the water at the soil surface cools until the nucleation temperature is reached. Ice then forms, at which point water below 0°C quickly freezes, resulting in an initial high rate of crystal growth. The rate then slows down as the water has to be 'pulled' from further down the soil profile and cooled.

The subsequent decrease in growth rate may be a result of (4):

i) The growth of ice needles insulates the soil surface, and thus heat removal from the surface is reduced.
ii) The thickness of the base of the ice columns increases. This causes the rate of growth to slow because a greater volume of water is then required to increase the length of the needles by a given amount.

The rate at which needle ice grew also seemed to be influenced by the moisture content of the soil near the soil surface. Figure 3 shows how crystal length and the moisture content near the soil surface varied with time for one experiment. After about three hours the ice nucleation temperature was reached and needle ice growth began. After the initial rapid rate of growth (explained above) the rate of needle-ice growth slowed and then remained fairly constant, as did the moisture content near the soil surface. Fourteen hours into the experiment, however, the soil-moisture content decreased to 27% (which is below the critical moisture content required for ice segregation in this soil). Thus needle-ice growth stopped and did not recommence for the remainder of the experiment. Examination of the specimen showed that the soil underneath the needles had frozen in-situ.

3.2 Varying types of growth profile

Two types of profile were observed; a relatively smooth pattern (Figure 4) and an intermittent pattern (Figure 5). Both types of profile could produce clear needle ice or needle ice that contained sediment particles (see Section 4).

In the laboratory both clear and 'dirty' crystals were produced in experiments showing a 'smooth' growth profile. Clear needles were produced under near-perfect growth conditions with a high soil-moisture content and final soil-surface temperatures in the range -1 to -4°C. It is assumed that the heat removed

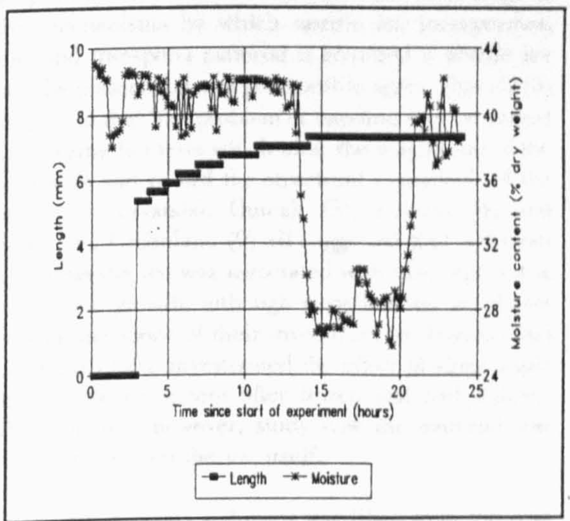

Figure 3: Needle-ice growth showing the influence of soil moisture content

at the soil surface was matched by the heat flowing to the freezing front with the soil moisture, allowing continuous ice segregation as Outcalt (3) envisaged. The formation of dirty crystals is discussed in Section 4.2.

An 'intermittent' pattern of growth, characterised by breaks in needle-ice growth, was usually followed by a rapid increase in the height of the crystal. Two types of crystal were formed with an intermittent growth profile:

i) Clear crystals, with no apparent banding.
ii) Crystals that contained distinct layers of sediment (Section 4.1).

The interruptions in the growth of crystals with no banding do not seem to correspond with disturbances in the soil-surface temperature. Thus, the breaks in growth may be associated with the arrival of discrete 'parcels' of water at the freezing front, although their passage was not observed in the moisture profiles. It has been suggested (13) that unsteady water flow can occur during needle-ice growth, which may influence the flow of heat to the soil surface. Water flux pulses are thought to be common during late evening/early morning (13). Outcalt (13) suggested that these water flux pulses cause disturbance to needle-ice growth. If the water flowing to the freezing front is warm enough it may increase the temperature at the freezing front so that it rises above 0°C, and stops needle-ice growth. When the temperature again falls below 0°C there will be a sufficient supply of water at the soil surface so that needle-ice growth recommences at a rapid rate. This could explain why no soil banding was observed within the ice needles, because the freezing front never descended into the soil.

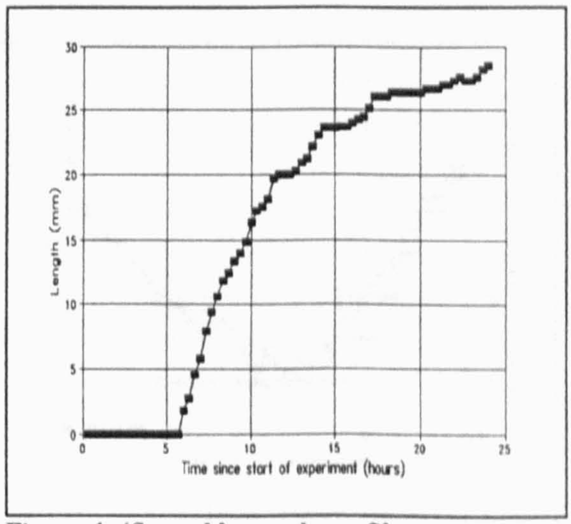

Figure 4: 'Smooth' growth profile

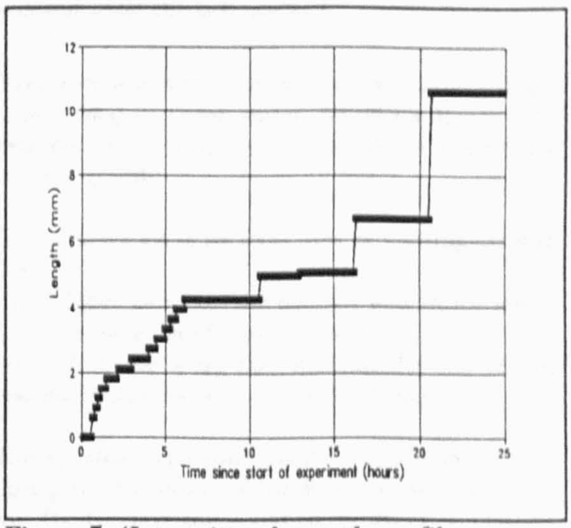

Figure 5: 'Intermittent' growth profile

4 SEDIMENT DISTURBANCE BY NEEDLE ICE

As stated above, needle-ice crystals can be either clear or contain particles of sediment. Study of the sediment lifted or incorporated by the needle ice is thought to be important in two respects:

i) It gives an indication of the growth history of the needle ice.
ii) The disturbance of the soil surface by needle ice causes the formation of small landforms such as soil

stripes and also results in soil erosion. Knowledge of the mechanisms by which needle ice incorporates, lifts and transports material is required if needle ice is to be understood as a geomorphic agent. Outcalt (3) suggested that 'the problem of banding may be solved by freezing lab tests which alter the magnitude of the heat sink and record the structural evolution' (of the needle-ice crystals). Outcalt (3), Fukuda (4) and Soons and Greenland (9) all suggested that sediment lift by needle ice was associated with interruptions to needle-ice growth, although experimental proof was outside the scope of their investigations. Higashi and Corte (10) have investigated the effect of slope angle on particle movement after frozen soil had thawed. They did not, however, study how the material was incorporated into the ice itself.

In the experiments sediment was lifted from the host sample by needle-ice growth in four ways:

i) As distinct bands of soil within the needle ice, producing multitiered crystals.
ii) Dispersed throughout the crystal, producing dirty needle ice.
iii) As a soil cap pushed up by the ice needles.
iv) As aggregates pushed up between dispersed needle-ice crystals.

Each of these seemed to be produced when there was disturbance in the needle-ice growth environment, which influenced the location of the freezing front. This disturbance was related to a reduction of moisture near to the soil surface and/or a decrease in soil-surface temperature. Each of the four types are discussed below.

4.1 Multitiered needle ice

Multitiered needle ice consists of needles that contain one or more distinct bands of sediment within the ice. Results from the present experiment seem to agree with the hypothesis discussed above, i.e. that disturbance in the growth environment causes the incorporation of sediment into needle ice. Disturbance in the experiments was introduced by either changing the input of heat from the heating coil or limiting the water supply to the sample.

Figure 6 shows needle-ice length and soil-moisture content near the soil surface during an experiment which produced needle ice with one sediment layer between two layers of clear needle ice. In this simulation it appears that soil-moisture supply was the limiting factor. Needle-ice growth stopped when the moisture content fell below 27.5% (dry weight) and recommenced once it rose again to about the same value. As the range of moisture values in this experiment was not very large it appears to show how critical moisture content is for controlling needle-ice growth.

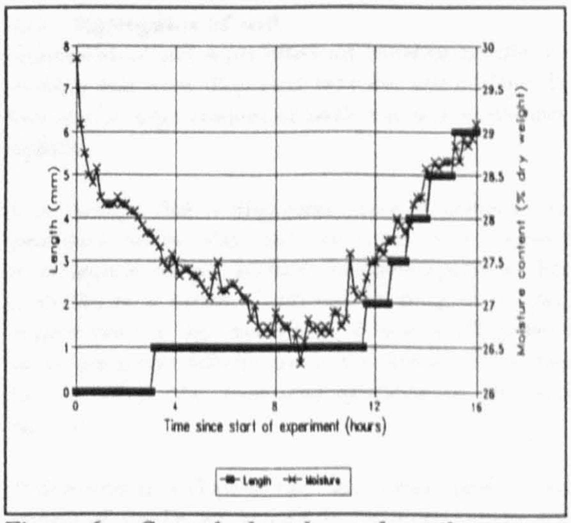

Figure 6: Crystal length and soil-moisture content near the soil surface

Needle ice is a form of ground ice and can be thought of as analogous to ice lenses, for which Martin (14) presented a four-stage cycle as a basis of a theory for ice lens growth:

i) Nucleation of ice away from an existing freezing front.
ii) Rapid growth of the nucleus into an ice lens.
iii) Termination of crystal growth.
iv) Heat and water flow between the end of (iii) and the beginning of a new cycle at stage (i).

This situation is probably similar to that which occurs during the formation of bands of soil within needle ice. The bands of soil would be incorporated between stages (iii) and (iv).

Takagi (15) presented a similar argument to explain the formation of ice lenses in soil. He stated that ice-lens formation was a problem of the simultaneous flow of heat and water within appropriate boundary conditions. For needle-ice growth it is suggested that there is a threshold which represents the critical soil-moisture content required to allow needle ice to form. This has to be maintained by a flux of soil moisture that brings sufficient heat to balance the heat removed from the soil surface by freezing. If the threshold is crossed when air temperature or moisture flux decreases, then in-situ freezing occurs. Thus, it appears that for particular heat flow conditions a particular soil-moisture flux is required. The frequency with which this threshold is crossed seems to control the type of needle ice that is formed in a given freezing cycle. Multitiered ice is formed when the temperature or soil-moisture content fail to exceed the critical threshold on only a few occasions during a freezing event. In-situ freezing may occur for several hours before segregation recommences.

4.2 Dirty needle ice

Dirty needle-ice crystals are crystals that have particles of sediment dispersed throughout the ice, giving the crystal a uniform brown colour. The processes described in Section 4.1 also seem to cause in the formation of dirty needle ice, although the disturbance to the heat flow is at different spatial and temporal scales. Indeed, Outcalt (3) suggested that dirty needle ice was formed as a result of spatially heterogenous ice intrusion or spatial-temporal branching if soil moisture within the soil was limited.

Results from the present study support the view of Outcalt. The incorporation of individual particles into the ice crystals seemed to occur when conditions were at the threshold between growth and no-growth, i.e. when conditions frequently cross the threshold by the process described in Section 4.1. The scale of the process, however, is much smaller both spatially and temporally than that causing multitiered needle ice. In-situ freezing only occurs for a very short period and the freezing front probably descends only a fraction of a millimetre.

These growth pulses were not observed on the growth profiles, however, which were recorded at ten minute scanning intervals. Future experiments will record needle-ice length at shorter intervals in an attempt to find these pulses in growth.

4.3 Soil caps

In some instances needle ice was produced which had a 'cap' of soil on top of the needles. These soil caps were either unfrozen or frozen. The former were produced when the soil surface was very dry (3 to 15% soil-moisture content at the start of the experiment). Whereas the latter were formed at moisture contents between 15 and 25%, where it is believed that there was enough water for ice nucleation, but not segregation. It is assumed that the freezing front descended into the soil until there was enough moisture for ice segregation.

The thickness of both types of cap is determined by the location at which ice segregation commences. The lower down that segregation occurs, the thicker the soil cap.

4.4 Aggregates of soil

Aggregates of soil were lifted up between needle-ice crystals that were dispersed over the soil surface. In this way a large amount of sediment was sometimes uplifted.

It is thought that a dispersed cover of needles was produced when the soil moisture and thermal conditions at the soil surface were heterogeneous. For example, as a result of uneven watering of the soil surface prior to the experiment, or due to differences in the grain size distribution of the sample. These two factors affect the frost susceptibility of the soil surface.

Differences in soil properties may cause preferential growth of needle ice at certain locations on the soil surface. Where the soil is more frost susceptible less supercooling will be required to produce ice nucleation (16). Those crystals that nucleate first may then be a moisture sink for the surrounding soil and prevent ice nucleation in adjacent areas. In this way crystals can grow to a considerable length, and material is often pulled up between the ice needles.

5 CONCLUSIONS

In experiments needle ice can grow with either a 'smooth' or 'intermittent' growth profile. Intermittent growth profiles were produced in experiments that showed either clear needle ice or needle ice that contained bands of sediment. Intermittent growth profiles are thought to grow when there is a disturbance to the growth environment which affects the stability of the freezing front, as a result of an imbalance of heat or moisture flowing to and from the freezing front. Clear needle ice is thought to form under steady external conditions, and the periods of no growth are caused by too much heat flowing to the freezing front.

Sediment can become incorporated into needle ice, and may give an indication of the growth history of the needle ice. Sediment incorporation usually indicates that the freezing front has descended into the soil, as a result of the disturbances described above. Different spatial and temporal scales of disturbance result in the formation of different types of needle ice.

The disaggregation of the soil by lift and/or incorporation by needle ice is an important stage in the process of soil erosion in many parts of the world. Needle ice can also cause the transport of material downslope, and this will be investigated in a future series of experiments.

The apparatus is also being modified to ensure more even wetting of the soil surface, and a method of monitoring soil moisture without disturbing soil-moisture flux is being sought. A reduction of the scanning time interval will also allow processes fluctuating more rapidly to be studied.

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